The Influence of Management Strategies on the Water Productivity in Dairy Farming and Broiler Production

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Equations

Nomenclature of abbreviations and symbols used

°C	degree Celsius
%	percent
a	annum, year
AMS	automatic milking system
ATB	Leibniz Institute for Agricultural Engineering and Bioeconomy
CO_2	carbon dioxide
d	day
DM	dry matter
e. g.	exempli gratia, for example
et al.	et alii, and others
etc.	et cetera
FCM	fat corrected milk (4 % fat, 3.4 % protein)
FTP	file transfer protocol
g	gram
$g_{protein}$	gram protein
h	hour
ha	hectare
HBP	herringbone parlour
kg	kilogram
kg_{cm}	kilogram carcass mass
L	liter
LCA	live cycle assessment
m	meter
m^2	square meter
m^3	cubic meter
MJ	mega joule
R^2	coefficient of determination
t	ton
$W_{drink-cow\_daily}$	daily drinking water intake of a cow
W_{input}	water input
$W_{input-clean}$	water input of cleaning
$W_{input-drink}$	water input of drinking
$W_{input-drink-broiler}$	drinking water demand per broiler chicken

$W_{input\text{-}feed}$	water input of feed production
$W_{input\text{-}parent}$	water input of the parents
W_{irri}	irrigation water
$W_{prec\text{-}transp}$	transpiration from precipitation
$W_{tech\text{-}barn}$	technical water in the barn
WP	water productivity
WP_{feed}	water productivity of feed dry matter
$WP_{feed\text{-}energy}$	water productivity of feed energy
$WP_{feed\text{-}protein}$	water productivity of feed protein
WP_{milk}	water productivity of milk
$WP_{milk\text{-}energy}$	water productivity of milk energy
$WP_{milk\text{-}protein}$	water productivity of milk protein
$WP_{milk\text{-}revenues}$	water productivity of milk revenues
$WP_{poultry\text{-}energy}$	water productivity of poultry meat energy
$WP_{poultry\text{-}meat}$	water productivity of poultry meat
$WP_{poultry\text{-}protein}$	water productivity of poultry meat protein

Abstract

Livestock production is the main user of water resources in agricultural production. Water is used in animal production for producing feed, watering the animals, and cleaning and disinfecting barns and equipment. The objective of this dissertation was to quantify the effects of management strategies, such as feeding, intensity of production and the replacement process on the water productivity of milk and poultry meat in Germany.

Water productivity in milk and broiler production systems was calculated based on the methodology of Prochnow et al. (2012). Own measurements of the drinking and cleaning water demand in milk production were conducted in a dairy cow barn. The study was based on site conditions of North-East Germany with common variations in farm operations.

The feed production is the main contributor to water input in dairy and poultry production. The water productivity of milk increased with an increasing milk yield. The most beneficial conditions related to water productivity in dairy farming were found to be with a milk yield of approximately 10,000 kg fat corrected milk and a grass silage and maize silage based feeding. The total technical water use in the barn makes only a minor contribution to water use. Former regression functions of the drinking water intake of the cows were reviewed and a new regression function based on the ambient temperature and the milk yield was developed. In broiler production the intensification of the fattening systems did not increase water productivity.

An increase of water productivity in animal production can be achieved with various management strategies with their specific influence on the production process. The feed management should be a focus of the strategies.

1 Statement of the problem

The expected increase in world population of up to 10 billion people will reduce the available water resources by half to 6300 m³ per capita by 2050 (Lutz et al., 1997; Ringler et al., 2010). The larger world population and the change in diets will lead to an increasing food demand by 70 to 90 % by 2050 (Rosegrant and Cline, 2003). Agriculture will compete with industrial and domestic users for water resources (Pimentel et al., 1997). Human diets will change to include more animal products, such as milk, meat and eggs (Delgado, 2003). The conversion of energy and protein from plants into animal products is connected with a loss of energy and protein in the animal product so that the water demand per MJ food energy and g protein will be higher than that for plant products. Animal products in human nutrition are subject to restrictions such as availability, costs, compatibility and religion.

Studies on management strategies to increase the water productivity of animal production on the farm-level in Germany are rare (Drastig et al., 2010). Studies about water use for the cleaning and disinfection of barns are scare and are of interest mainly to public authorities and consulting agencies (Jensen, 2009; KTBL, 2008; Rasmussen and Pedersen, 2004; Schuiling et al., 2001; Steward and Rout, 2007; Williams, 2009). In most of the studies the estimation of the demand for cleaning water is not described in detail. Studies on the drinking water intake of dairy cows were made only for early and mid-lactation and do not cover the end of the lactation. Concepts on improving the water productivity were developed mainly for milk (Descheemaker et al., 2010; Haileslassie et al., 2009) and beef (Peters et al., 2010) and not for poultry; the regions investigated were Africa, America, Asia and Oceania (Armstrong et al., 2000; Descheemaeker et al., 2010; Haileslassie et al., 2009; Haileslassie et al., 2011; Moore et al., 2011; Renault and Wallender, 2000; Rockström et al., 2010; Singh et al., 2006; Zonderland-Thomassen and Ledgard, 2012). Dairy farming includes the production of feed, milk, meat and replacement and is the most complex kind of livestock farming (Descheemaeker et al., 2010; Kraatz, 2012). The water productivity of poultry has a wide range owing to the different regions investigated and to the climate conditions and predominant keeping conditions (Chapagain and Hoekstra, 2003; Renault and Wallender, 2000).

The production conditions in Germany, such as the availability of feed and the high yield of the animals, were not covered. The allocation of the water use to the output will influence the effect on the water productivity when feeding residues. Increasing the yield of the animals by breeding with better genetics is one way to increase the water productivity as described in the literature for regions with a low yield of the animals. Not all existing recommendations are applicable for German conditions with a great effect on the water productivity, such as crossbreeding or improving the veterinary service.

2 Overall objectives

The objective of this dissertation was to quantify the effects of management strategies, such as feeding, intensity of production and replacement process, on the water productivity of milk and poultry meat in Germany. In particular, the breeds, yield and diets of the animals shall be investigated with regard to the water demand per kg of milk, kg of broiler meat, g of protein and MJ gross energy. Another focus was put on the drinking and cleaning water demand in a dairy cow barn and a broiler chicken barn. The aim of the investigations was to identify management options with high water productivity in the supply of animal products for human consumption.

3 State of the art

3.1 Water flows on farm scale

The spatial system boundaries of farms can be defined according to Prochnow et al. (2012): The system includes any physical thing which belongs to the farm. The fields cultivated by the farm and the areas with farm infrastructure are included in the horizontal boundaries of the system. The area between the fields of the farm and the farm infrastructure, such as rivers, forests, or public areas, do not belong to the system. The vertical boundaries are the height and the depth of the plants, animals, buildings, machines and equipment. The vertical boundaries can change, while the plants grow and get harvested and the animals and machines move.

Water enters and leaves the farm in different ways. In Figure 1 the water flows on farm scale are shown according to Prochnow et al. (2012). The water enters the farm via precipitation, surface water, irrigation water, tap water, sub-surface flows, table rising and capillary rise. Water can also enter the farm directly or indirectly when it is bound or used to produce products which enter the farm; these are called pre-chains, and include machines, buildings, equipment, purchased feed, etc. The single types of water inflow play different roles in the conceptual scheme of estimating water demand described below. In some studies the water inflow was subdivided even further.

The water leaves the farm as it enters the farm or is used or is transformed or is bound in products. The ways water can leave the farm include plant transpiration, evaporation, interception, deep percolation, runoff, water bound in product, waste water and lateral flows.

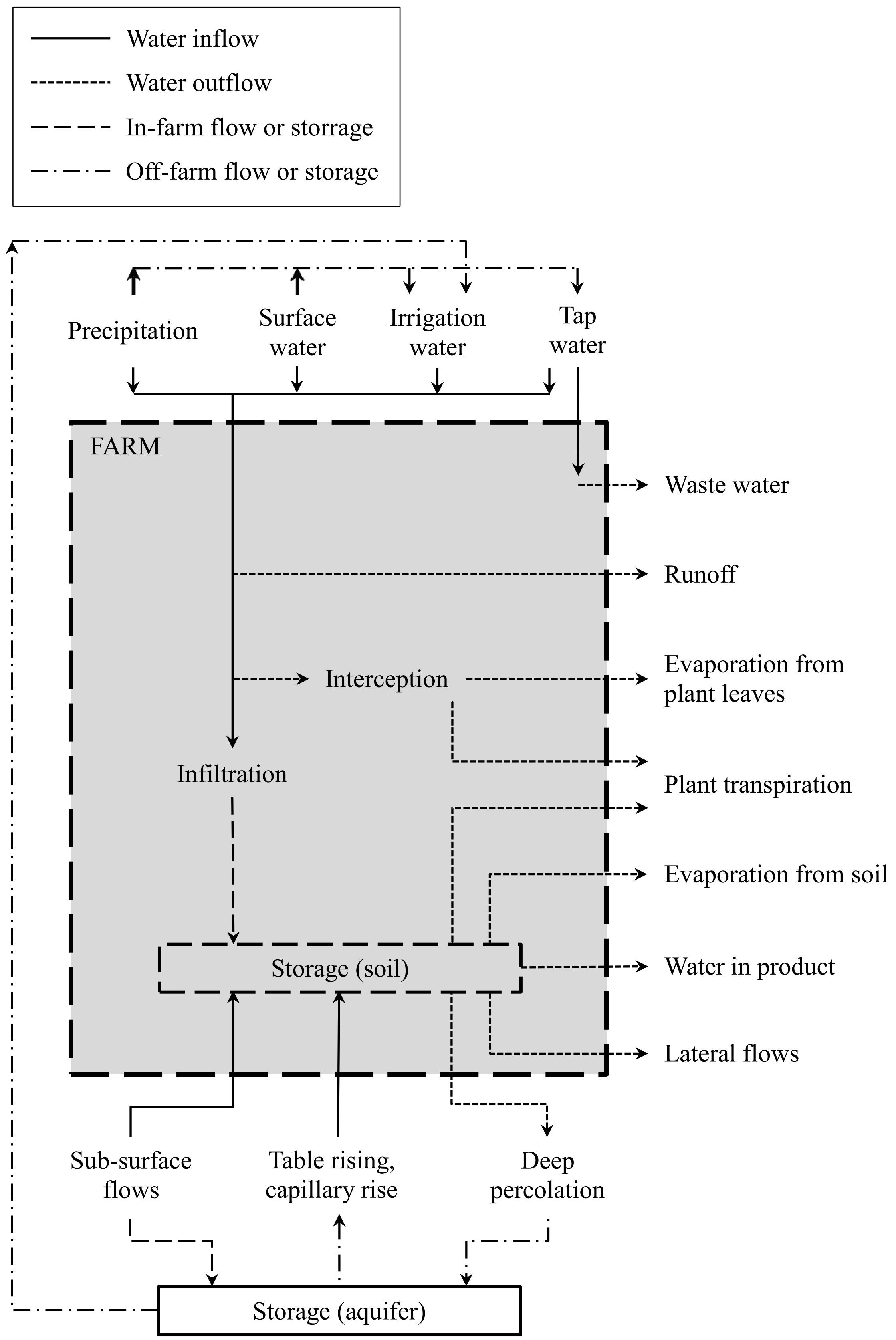

Figure 1: Water flows and storages on farm scale (Prochnow et al., 2012 adapted)

3.2 Concepts

3.2.1 Overview

There are several methods to express the relation between the water demand and the output of a farm. A standardized definition has not yet been set. This can be seen in the different terms used for water, which are included in the calculations: blue water, capillary rise, consumptive water, deep percolation, evaporation, evapotranspiration, green water, grey water, ground water, interception, irrigation water, precipitation, productive water, transpiration, subsurface water, surface water, tap water, technical water, waste water, water demand, water inflow, water input, water use, and so on. Some of the terms can be used as synonyms (e. g. consumptive water, water demand, water input, and water use) and some can be derived from the others (e. g. evapotranspiration is the compound of evaporation and transpiration).

The output of a farm is also defined in different ways. Most studies consider mass or monetary outputs of products (e. g. Kebebe et al., 2015; Moore et al., 2011; Singh and Kishore, 2004). Further outputs can be nutritional values such as food energy or protein (e. g. Molden et al., 2010; Renault and Wallender, 2000), drought power (e. g. Alemayehu et al., 2012; Kebebe et al., 2015), environmental services and livelihoods (e. g. Descheemaker et al., 2010). Some studies focus on single products, such as milk or grain (e. g. Bouman, 2007; Sultana et al., 2015; Zwart and Bastiaanssen, 2004), or the whole yield of the plants, such as grain and straw, or of the animals, such as milk, meat, leather and drought power (e. g. Cook et al., 2009; Descheemaker et al., 2010; Kebebe et al., 2015) or on aggregated outputs of whole farms (e. g. Haileslassie et al., 2009; Prochnow et al., 2012) or farming systems (e. g. Descheemaker et al., 2010).

There is no standard when the water input per output or the output per water input is in focus. The most common concepts are described in the following chapters with their definitions of water included in the calculations and the regarded output. The pros and cons for using them to calculate the water demand on farm scale are described.

3.2.2 Live cycle assessment (LCA)

Live cycle assessment (LCA) has its origin in estimating the environmental impact of industrial production on global value chains (Koehler, 2008) and was developed in the late 1960s (i Canals et al., 2009). The water use was not estimated in LCA in the initial period of its conceptual development because the concept was developed in countries with less water scarcity (Koehler, 2008). In the 2000s the total water amount in agricultural systems was estimated with LCA by i Canals et al. (2006). The main impact pathways of water in the study of i Canals et al. (2009) were: direct water use leading to changes in freshwater availability for humans leading to changes in human health; direct water use leading to changes in freshwater availability for ecosystems leading to effects on ecosystem quality; direct groundwater use causing reduced long-term freshwater availability; land use changes leading to changes in the water cycle leading to changes in freshwater availability for ecosystems leading to effects on ecosystem quality. The water use was regarded from cradle to grave, from the production of raw materials to waste management (Boulay et al., 2015; i Canals et al., 2009). The focus was on the environmental impact of the water use in agricultural production. Precipitation is not taken into account since it generally has no impact on the environment (de Boer et al., 2013; i Canals et al., 2009; Koehler, 2008; Peters et al., 2010; Pfister et al., 2009). The indirect water, which is used to produce machines, buildings and equipment, has a negligible part of the total water demand (Döring et al., 2013), but is taken into account, too. LCA studies do not distinguish between the source of the water and the way the water leaves the system. Until now, most of the LCA studies on water use of agricultural products used a kg product as functional unit.

In contrast to other concepts, LCA aims at the assessment of environmental impacts of water use. Consequently, only those fractions of water use that cause environmental impacts are included in the inventory. Since precipitation is excluded, LCA is not suitable to be applied beyond its original intention for recommendations on farm water management and improvement of water productivity in rain-fed agricultural systems.

3.2.3 Virtual water - Water footprint

In the literature, the term “water footprint” is used with different meanings. A standard was set with ISO 14046.2 (2014) whereby the water footprint quantifies the potential environmental impacts related to water using the concept of LCA. More than a decade before that, the virtual water concept was developed, also using the term water footprint but without an environmental impact assessment. Hence the water footprint described in this chapter is not consistent with the later developed ISO 14046.2 (2014).

The term “virtual water” was introduced in the 1990s with regard to food (Allan, 1993; Allan, 1994; Allan, 1998), proposing that food trade implies the trade of virtual water and therefore could be a means of balancing between water abundant and water scarce regions or nations. The concept has been elaborated in the following years by developing a more detailed methodology to estimate the amount of virtual water contained in a product. According to

Chapagain and Hoekstra (2003), virtual water is defined as the amount of water which is required to produce a commodity or service. The water footprint concept according to Chapagain et al. (2006) distinguishes between green, blue and grey water. Green water is evapotranspiration from precipitation, blue water is evapotranspiration from ground and surface water and grey water is water that would theoretically be needed to dilute polluted water (Chapagain et al., 2006). The evapotranspiration was considered as the main contributor of water use (Chapagain et al., 2006). Chapagain and Hoekstra (2003) consider three components of virtual water of a live animal. These are the virtual water content of consumed feed, drinking water and service water. The water content of feed has two parts: the water to prepare the feed mix and the water which the feed ingredients needed to be produced.

The benefit of water footprint is the estimation of the volumetric use. Since it does not consider environmental impacts, extensions of the methodology or combination with LCA are discussed (Ridoutt and Pfister, 2013). The applicability to derive recommendations on farm water management is limited. The concept is not designed to be used on the farm scale to reflect agricultural management measures. The virtual water includes not only the productive water which is needed to generate biomass, but also the theoretically available water, which can leave the farm by unproductive evaporation.

3.2.4 Water productivity (WP)

The water productivity is generally defined as the relation of output to water input (Bouman, 2007). A meticulous description of determining water input and output is needed to make results comparable (Bessembinder et al., 2005). The water input can include the evaporation, transpiration, irrigation water, drinking water, service water, etc. (Bessembinder et al., 2005). The output can be the fresh or dry mass of the product or its economic value (Bessembinder et al., 2005). The output can also be displayed on a feed or food energy and feed or food protein basis (Renault and Wallender, 2000). Studies of water productivity in agricultural production were developed for crop production first (Bouman, 2007; Bouman and Tuong, 2001). Later, the concept of livestock water productivity was developed by Peden et al. (2007). The livestock related merit was defined as the output of the system (Cook et al., 2009; Descheemaeker et al., 2010; Peden et al., 2009). Prochnow et al. (2012) defined water use indicators on farm scale. One of these indicators is the farm water productivity. The water input is transpiration from precipitation, technical water and indirect water. The output is fresh mass, dry mass, food energy and monetary value (Prochnow et al., 2012). The evaporation from precipitation was excluded from the estimation of the water productivity, but was included in the estimation of the degree of water utilization (Prochnow et al., 2012).

The concept of farm water productivity from Prochnow et al. (2012) was chosen to calculate the influence of management strategies on water productivity in dairy farming and broiler production. This concept was seen as the most suitable method to calculate the water productivity on the livestock stage of production, since it focuses on productive water, which is needed to generate biomass (Pereira et al., 2012)

3.3 Allocation of the water demand to the output

An allocation of the input to the output is needed in systems with more than one regarded output. The allocation has an important role in the height of water productivity. The influence of the calculation of the water use on water productivity was described above. The definition and allocation of the output to the water input is described below. Plants can be harvested in whole or in parts. For maize silage nearly the whole above ground biomass is harvested. For wheat the grain and the straw could be harvested when the straw is used as feed or litter material for the barn. Soy beans are normally planted to get the oil. The soy bean meal is sold as a protein-rich feed. The water demand of the soy beans could be allocated altogether to the main product oil so that no water use is allocated to the soy bean meal as by-product. The allocation could be done on a mass, monetary, energy or protein base. As a rule, an animal supplies not only one product. In most of the cases animals have two or more benefits. A dairy cow produces milk, meat, leather and in some regions they are used as draft animals. Therefore, the water demand has to be allocated to the different outputs. Laying-hens produce eggs and meat. Another part is the water which is needed to replace the old animals. Not every calf or chick will give milk or lay eggs. Young animals also need water and not only in the productive phase of their lives. All the different ways to allocate the water demand of production to the output have their justification, but it has to be determined to which output the water demand should be allocated.

It is also necessary to allocate the water demand of the plants to the output of feed. Not all plants are fed in whole to the animals. A lot of plants are processed to food first and the residues are then used as feed for the animals. From soy beans the oil is extracted first and the rest is used as protein-rich feed. From sugar beets the sugar is extracted and the beet pulp silage is fed to cows and pigs. Rape seed meal, draff, pomace and bran are typical by-products in German animal feeding as well. If the water demand is allocated solely to the main product, the by-products have no water demand in the calculations. This may be a way to increase the water productivity, but the production of these by-products needs water too. Nevertheless, feeding by-products is a way to convert products unsuitable for human nutrition into high quality animal products.

3.4 Ways to increase the water productivity in livestock production

There are different ways to increase the water productivity of vegetal and animal products. An increase in water productivity could be achieved with an increased output with the same amount of water input or the same output with less water input or a combination of both options (e. g. Bossio et al., 2010; Molden and Sakthivadivel, 1999; Prochnow et al., 2012; Renault and Wallander, 2000). “The most important performance indicator in many countries” is the concept of water productivity with more “crop-per-drop” (Perry, 1999). The improvement of water productivity was investigated in different regions with their specific conditions: in Africa by e. g. Descheemaeker et al. (2010), Haileslassie et al. (2009), and Rockström et al. (2010), in America by e. g. Renault and Wallender (2000), in Asia by e. g. Haileslassie et al. (2011), and Singh et al. (2006) and in Oceania by e. g. Armstrong et al. (2000), Moore et al. (2011), and Zonderland-Thomassen and Ledgard (2012). For Western Europe a case study of Prochnow et al. (2012) is available.

Feed production contributes the most to the total water input in livestock production (Singh et al., 2003). Feed and animal management have a high potential for increasing the water productivity in livestock farming (Descheemaeker et al., 2010; Drastig et al., 2010). Decreasing the water demand can be realized by reducing unproductive losses, for example, the evaporative part of the precipitation and the irrigation water. In livestock production the water demand of the feed can be decreased by using feed with high water productivity (Descheemaeker et al., 2010). Another option is reducing conversion losses by reducing the share of maintenance and increasing the share of water for yield. Not all options of increasing the water productivity are suitable for all production systems in the different regions. The improvement of water productivity is described below for dairy farming as the most complex type of livestock operation (Descheemaeker et al., 2010; Kraatz, 2012). An increase of water productivity at Ethiopian conditions was observed with an increase in performance of the cows, since the share of maintenance related to the performance on total demand is reduced (Peden et al., 2009). A similar effect was observed by Haileslassie et al. (2011) in the Indo-Ganga basin and by Armstrong et al. (2000) in Australia. In Africa the water productivity of milk could be increased with more veterinary service, breeding, and greater supplies of feed and drinking water (Descheemaker et al., 2010). Veterinary service can reduce the mortality of the cows and the cows therefore have more useable milk. The local breed could be crossbred with higher yielding breeds. With this improvement of genetics, the demand for maintenance is shared on more output. In German dairy herds these options are mostly utilized. To decrease the role of maintenance on total water input, the yield of the animals could be increased. But this option is limited, since high yield is genetically fixed, and to generate a high yield, the feed has to have a high quality. Such feed has reduced water productivity and so the effect of increasing the yield is limited.

The replacement process also needs water and in addition it has no output of milk. This phase of live should be as short as possible and the water should be allocated to as much milk as possible. Decreasing the age at first calving causes an intensive upbringing period and maybe a reduced milk yield in first lactation since the cow is not full-grown. The milk yield per cow in her lifetime is determined by two factors: the milk yield per lactation and the number of lactations. The milk yield cannot be increased in an unlimited way, as described before. The number of lactations can be increased with good servicing, genetics and veterinary care. The most important reasons why cows leave the farm are mastitis, infertility, lameness, low milk yield and metabolic disturbances (LKV BB, 2014). The replacement rate decreases with a longer life of the cows, but the genetic improvement decreases too. A decrease of the replacement rate from a low to a very low level increases the water productivity less than the genetic progress.

4 Water productivity of milk production

4.1 Preliminary remark

Chapter 4 is mainly based on Krauß et al. (2015a), which is part of this thesis, and can be found in Annex A. More details are given there.

4.2 State of the art and subject-specific aims

The water productivity of milk was investigated several times with different methods in various regions of the world. The focus regions were Africa, Asia and Oceania (e. g. Armstrong et al., 2000; Descheemaeker et al., 2010; Haileslassie et al., 2009; Haileslassie et al., 2011; Moore et al., 2011; Rockström et al., 2010; Singh et al., 2006; Zonderland-Thomassen and Ledgard, 2012). Dairy farming includes the production of feed, milk, meat and replacement and is the most complex kind of livestock farming (Descheemaeker et al., 2010; Kraatz, 2012).

The aim of this section was the quantification of management strategies in dairy farming on the water productivity of milk for North-East German conditions. Variation in feed, milk yield and replacement rate is the focus. A wide range of possible strategies for producing milk will be shown.

4.3 Materials and methods

4.3.1 System boundaries and data

The water productivity was calculated according to the concept of water use indicators at the farm scale developed by Prochnow et al. (2012). The water productivity of milk was analyzed from cradle-to-farm-gate. The water for feed production and the drinking water of the animals was taken into account since these are the main contributors to water demand in dairy farming (Singh et al., 2003). The production of fertilizer, machines and buildings were excluded from the calculations, since they play a negligible role on the total water demand (de Boer et al., 2013; Döring et al., 2013). The whole amount of water input was allocated to the milk, since it is the main output of the production system. The replacement was included in the calculations, because they were needed to recreate the dairy herd. Replacement means the calves and heifers.

Brandenburg, as a part of North-East Germany and with its early summer drought, was chosen as the study region. The study period were the years 2008 to 2010. A typical dairy system in that region has a herd size of 180 dairy cows and an average milk yield of 8,000 kg fat corrected milk (FCM) cow^{-1} $year^{-1}$ (Kraatz, 2012). The breed of the cows is mostly Holstein-Friesian. The average replacement rate of dairy cows in Brandenburg was nearly 40 % (LKV BB, 2011; LKV BB, 2014) and the age at first calving was 25 months (Spiekers and Potthast, 2004). The lactation period to reach the annual milk yield is 305 days. A 60-day dry period was taken into account, too.

The water productivity of milk is displayed in kg FCM (WP_{milk}), MJ food energy ($WP_{milk\text{-}energy}$), kg food protein ($WP_{milk\text{-}protein}$) and Euro ($WP_{milk\text{-}revenues}$) per m^3 of water input. The water productivity of feed is displayed as kg dry matter (WP_{feed}), MJ net energy for lactation ($WP_{feed\text{-}energy}$) and kg crude protein ($WP_{feed\text{-}protein}$) per m^3 of water input.

4.3.2 Water input and water productivity of feed

The water input (W_{input}) was defined as the sum of plant transpiration from precipitation, irrigation water and drinking water of the animals (Prochnow et al., 2012). The plant transpiration was calculated with the FAO 56 dual crop coefficient approach under nonstandard conditions (Allen et al., 1998). The calculations were done with the ATB Modeling Database which has a module which includes crop water stress and interception loss (Drastig et al., 2012; Drastig et al., 2013).

The arable land of Brandenburg was divided into four agricultural growing regions (LELF, 2010) and the pasture was divided into four yield groups. Four soil groups summarize the specific growing conditions of the arable land and the pasture. The soil overview map (State Office for Mining, Geology and Resources Brandenburg, 2001) was combined with the characteristics of the soil groups. As a result, 20,000 polygons were needed to indicate the different growing conditions, such as soil type with its specific characteristics, precipitation, sunshine duration, temperature, wind speed and so on.

The water productivity of 12 feed crops was calculated. The feed of the animals, produced in Brandenburg, was maize for grain, maize for silage, oats, permanent grass land (pasture and hay), rapeseed, rye grass (silage and hay), sugar beets, triticale, winter barley, winter rye and winter wheat. For soy beans Argentinean and Brazilian were taken into account.

4.3.3 Water input and water productivity of milk

The diets of the cows consisted of grass silage, maize silage, hay, pasture, beet pulp silage, soy bean meal, rape seed meal, triticale and concentrate. Maize grain, molasses, oats, rape seed meal, winter barley, winter rye and winter wheat were mixed and pressed into pellets and fed to the cows as a concentrate. The diets of the cows were presented as a total mixed ration.

A balanced standard diet for a milk yield of 8,000 kg FCM was considered as the base of the development of diets for other milk yields (Kraatz, 2012). The milk yield was varied between 4,000 and 12,000 kg FCM in steps of 2,000 kg to cover a wide range of production conditions. Another point of diet developing was the variation of the main ingredients of a diet with the same milk yield. The share of grass silage, maize silage or concentrate was maximized to the maximum of a ruminant appropriate feeding and to cover the nutritional demand of the cows, and also to investigate the effect of the feeding strategy on the water productivity of milk. The share of pasture in the diets was varied with the grazing in summer. During a whole-year confinement, the cows had no access to the pasture. At half-day grazing in summer, the diets of the cows contained 20 % pasture grass, and with full-day grazing in summer 40 %. The diets could be used on the farm to reach the expected milk yield. An adaption is needed if the energy and protein content of the on-farm feed differ from the assumed values. The replacement rate was varied between 10 and 50 % in steps of 5 %.

The drinking water demand of the cows was estimated according to Meyer et al. (2004) on a daily basis. The drinking water demand of the calves and heifers was calculated according to KTBL (2008).

4.4 Results and discussion

4.4.1 Water input and water productivity of feed

The transpiration from precipitation $W_{prec\text{-}transp}$ is shown in Figure 2 and the mean water productivity of the feed in Figure 3.

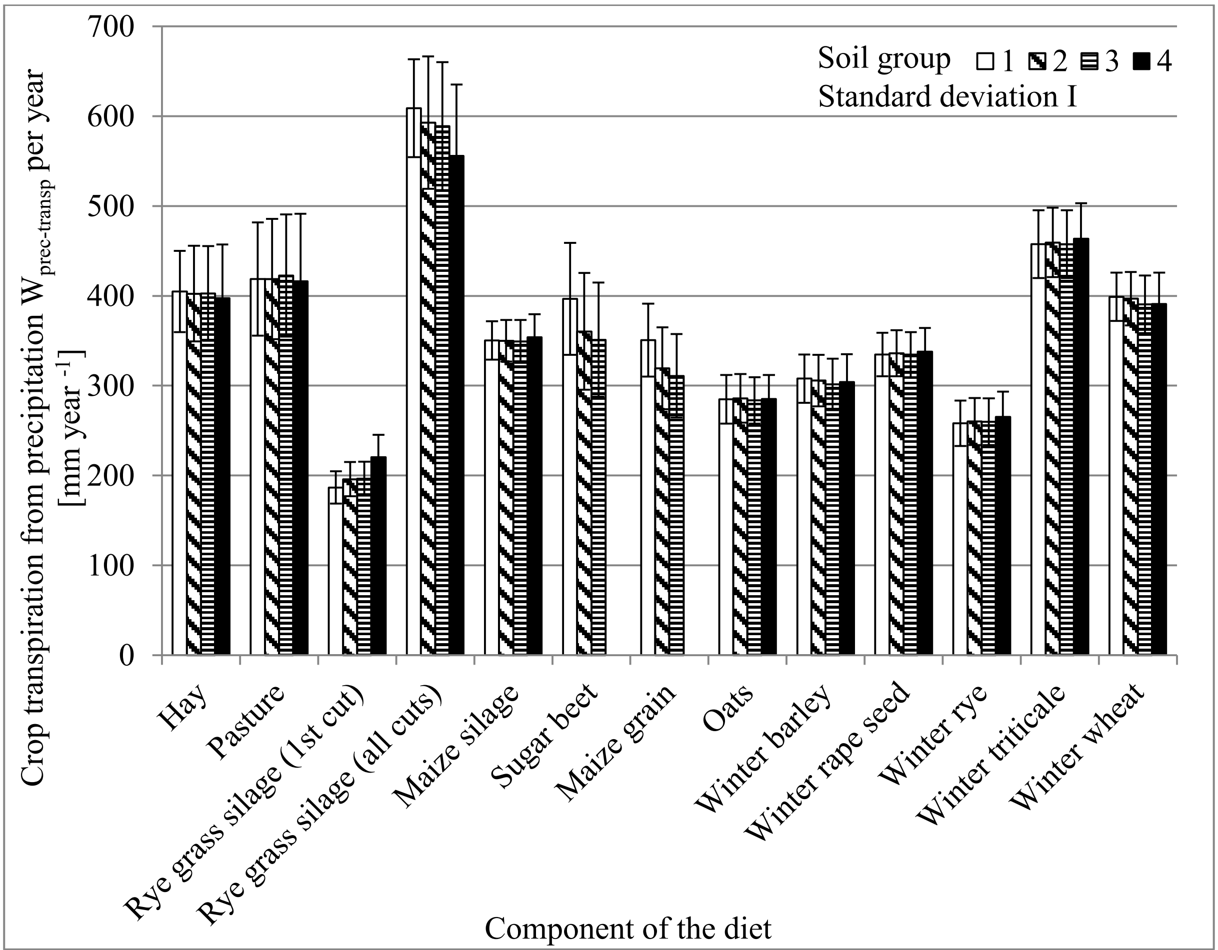

Figure 2: Transpiration from precipitation

The share of harvested products to total plant mass has an important influence on the mass-based water productivity, as seen with sugar beets and maize silage, which has the highest water productivity. Harvesting the whole plant is not suitable for all types of plants, since the straw of grain can be used in dairy cow feeding only in small amounts. So the water productivity of grain and concentrate is the lowest of the investigated feed stuffs. Among the investigated grains there are differences, too. Winter rye has nearly twice the water productivity of winter wheat. Winter rye is better adapted to the dry growing conditions, (Kottmann et al., 2016) which occur in the investigated area of Brandenburg, than winter wheat, and so winter rye can reach the same yield as wheat with less water.

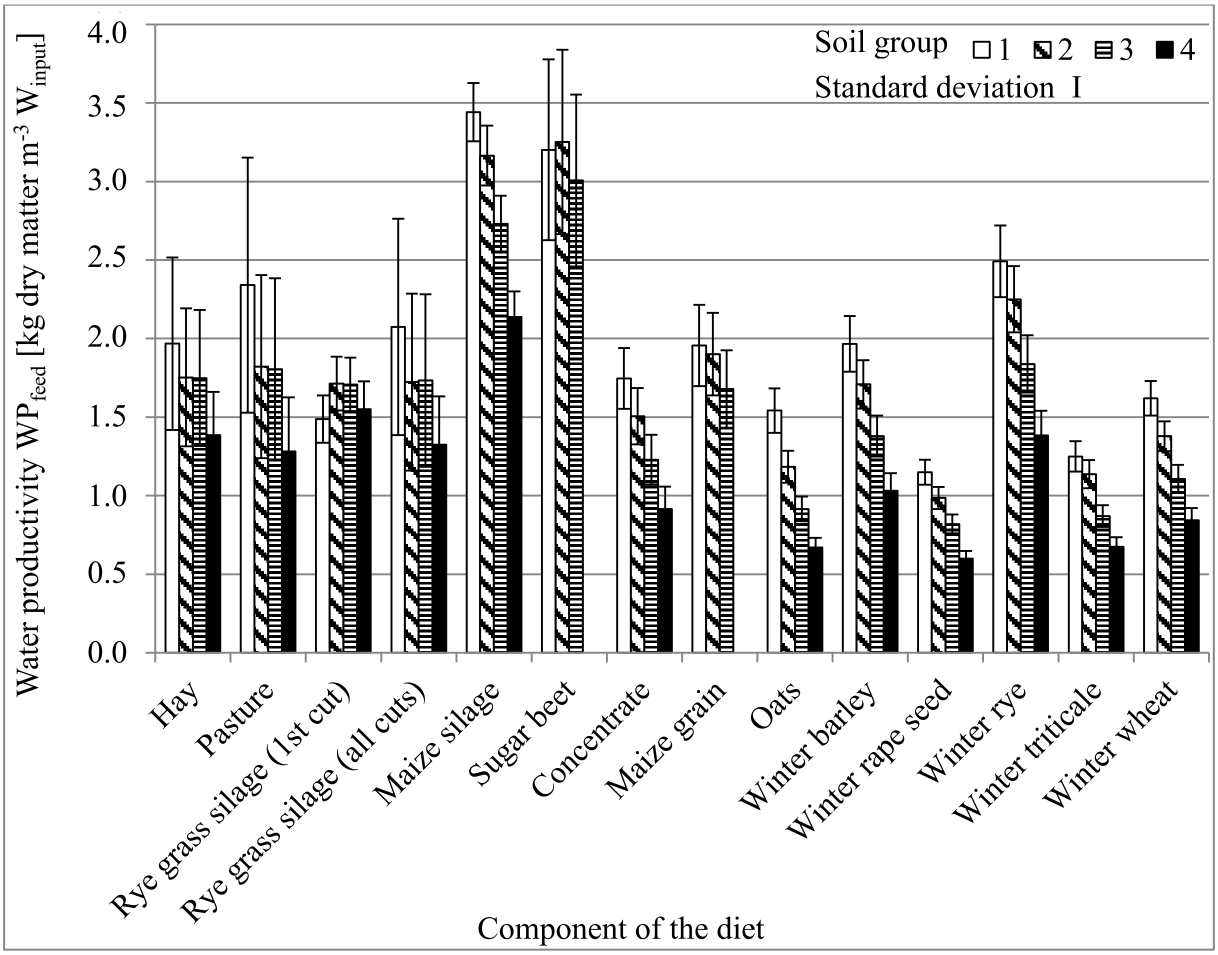

Figure 3: Mean water productivity of the components of the diet with different soil groups

Plants have a fixed water demand for the accumulation of carbon compounds, called water use efficiency (Hatfield et al., 2001; Passioura, 2006). The plants can be divided into a group of C3-plants and a group of C4-plants. The difference between these two groups is the way they accumulate carbon compounds. Light and CO_2 is needed for the photosynthesis. CO_2 enters and vapor leaves the plant via the stomata. High radiation causes a high CO_2-accumulation when the stomata are open. This causes a high loss of vapor. The plants close their stomata to reduce the loss of vapor and so no CO_2 can enter the leaves. C4-plants are adapted to the low CO_2 concentrations in the leaves, since they have their origin in the tropical zone of the earth (Furbank and Taylor, 1995). The adaption to radiation has another effect in the temperate zone. The stomata have not been closed that often and more CO_2 is available for the plant. More biomass can be generated with the same amount of water. Even more biomass could be generated when more water was available.

In Germany the need of saving water in plant production is not that urgent as in arid regions. The access to rain water is associated with the access to land. Irrigation water is taken from one's own wells and there are cheap water rights.

4.4.2 Water input and water productivity of dairy production

The total water input per cow per year including the water input of feed production, the drinking water, and the water input of the replacement is shown in Figure 4.

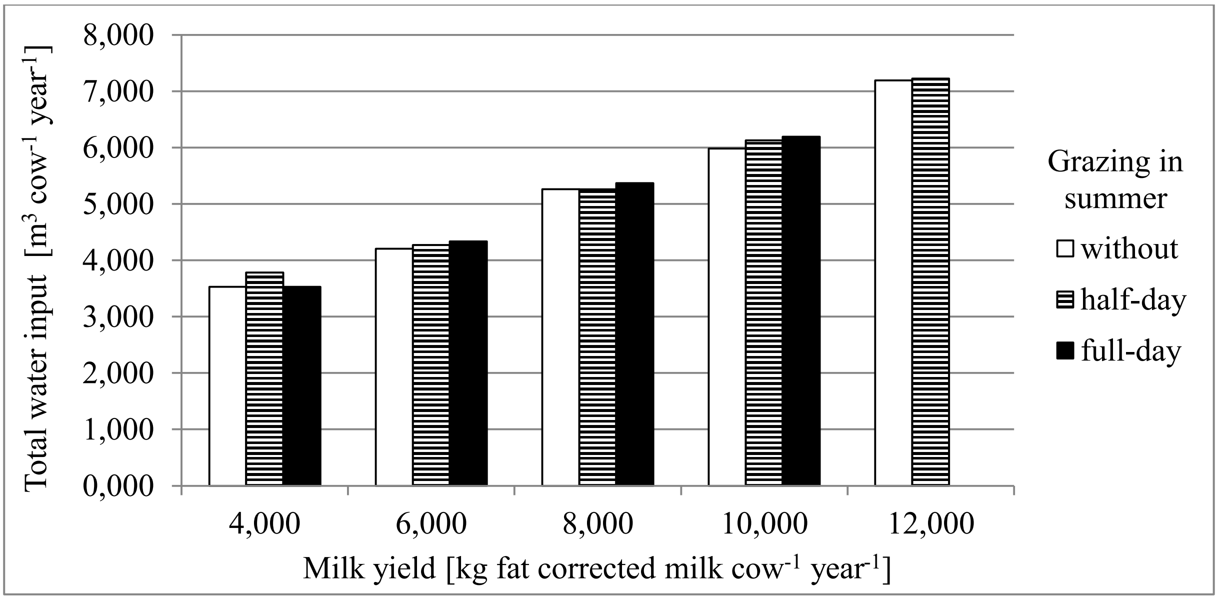

Figure 4: Total water input per cow per year.

The water input per cow per year increases with an increasing milk yield. This was expected since the demand for maintenance and yield and the feed intake increases. Grazing in summer had only a little effect on the water input. The share of the maintenance on the total energy and protein demand is shown in Table 1; it decreases with an increasing milk yield of the cows. The feed conversion into milk increases at higher milk yields (Descheemaeker et al., 2010; Zonderland-Thomassen and Ledgard, 2012) since the demand for maintenance and the demand for yield shifts to the demand for yield. The share of maintenance on the total demand should be low. At a given demand for maintenance and a higher output, the share of maintenance on the input would be lower. The remaining part of the input can be used to create the output. In the case of water a lower share of maintenance increases the water productivity. The difference between 4,000 and 6,000 kg FCM cow^{-1} year^{-1} is 7 % for the energy and 8 % for the protein. The difference between 10,000 and 12,000 kg FCM cow^{-1} year^{-1} is 2 % for the energy and 3 % for the protein. The effect of reducing the share of maintenance to the yield is more distinctive at low milk yields than at high milk yields. The share of maintenance on total energy demand at 4,000 kg FCM cow^{-1} year^{-1} is more than twice the share at 12,000 kg FCM cow^{-1} $year^{-1}$. On the total protein demand the share of maintenance at 12,000 kg FCM cow^{-1} $year^{-1}$ is 40 % lower than at 4,000 kg FCM cow^{-1} $year^{-1}$. A further increase of genetic potential by crossbreeding as described for African and Indian conditions is not a suitable way to increase WP_{milk} under German conditions (Descheemaeker et al., 2010; Haileslassie et al., 2009; Haileslassie et al., 2011).

Table 1: Share of maintenance on total energy and protein demand

	kg fat corrected milk cow $^{-1}$ year $^{-1}$				
	4,000	6,000	8,000	10,000	12,000
Share of maintenance on total energy demand	30 %	23 %	19 %	16 %	14 %
Share of maintenance on total protein demand	46 %	38 %	33 %	30 %	27 %

The water productivity of milk at different milk yields and feeding strategies is shown in Figure 5. The average WP_{milk} at a milk yield of 8,000 kg FCM is 1.5 kg FCM m^{-3} W_{input}. The WP_{milk} at 4,000 kg FCM is 30 % and at 6,000 kg FCM 10 % lower. An increase of the milk yield to 10,000, respectively, and to 12,000 kg FCM increases the WP_{milk} by 7 %. The highest WP_{milk} is found at 10,000 kg FCM with a grass silage based diet and without grazing in summer. As described above the share of maintenance on the total energy and protein input decreases not that distinctive at higher milk yield than at lower milk yields. The diets of the cows at 12,000 kg FCM have to have a higher energy and protein content than at lower milk yields, since the feed intake capacity is limited (Spiekers and Potthast, 2004). The higher energy and protein content of the diet is achieved with a higher share of concentrates. Concentrates have a lower WP_{feed} than roughage, as described in section 4.4.1 and e. g. by Blümmel et al. (2009). As a result, the effect of reducing the share of maintenance is counterbalanced by feeding more concentrates. A further increase in milk yield up to 14,000 kg FCM will not lead to an increase in WP_{milk}. Diets for a milk yield of 14,000 kg FCM would not ensure a ruminant-appropriate feeding under the given conditions with the live mass of the cows and the diet components, since the share of concentrates would be too high to maintain the function of the rumen.

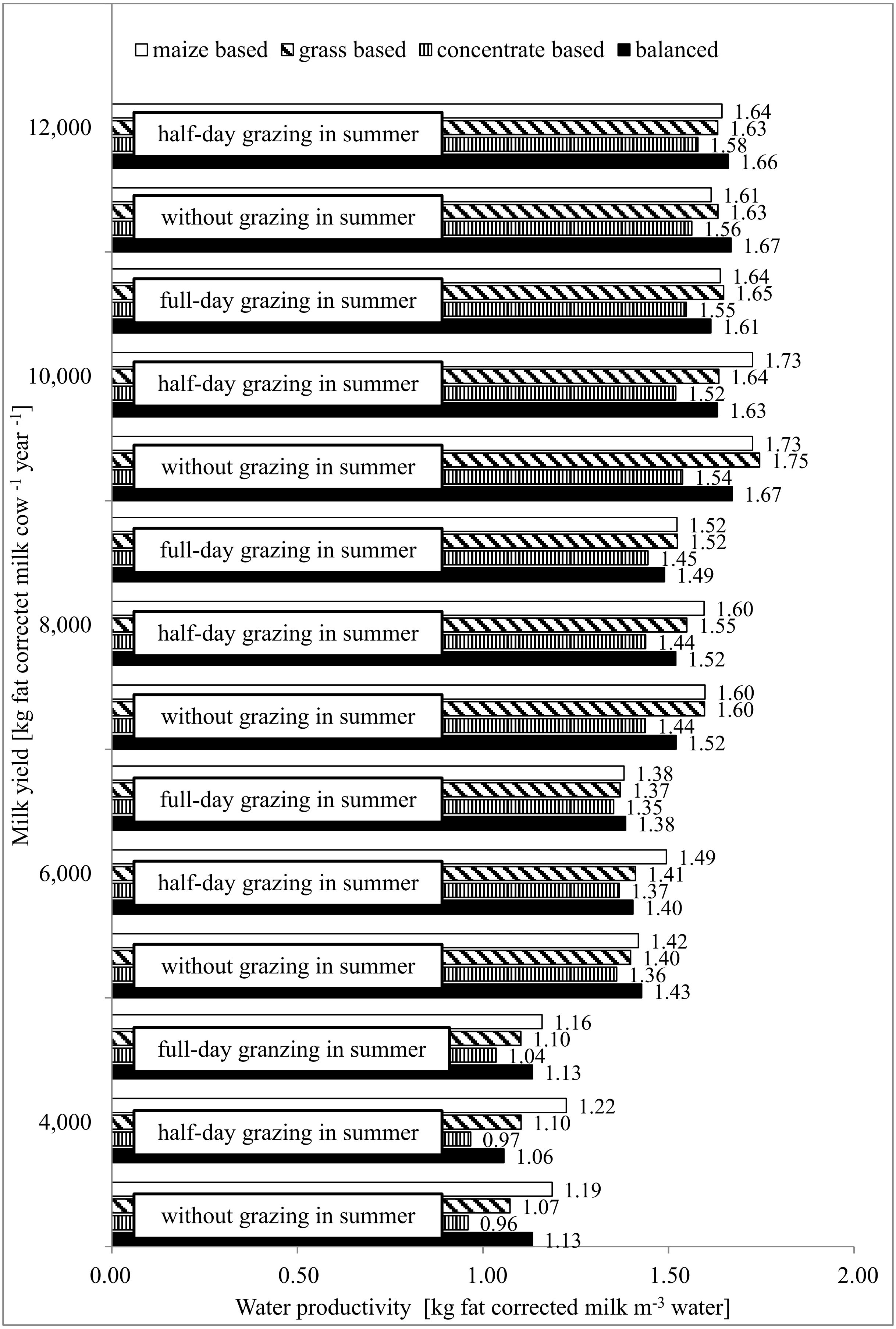

Figure 5: Water productivity of milk at different milk yields and feeding strategies

Saving water may not be the focus of a farm manager in Germany, since other internal and external factors influences the decisions. Agronomic measures will be the first way to decrease the water demand of feed production if water became scarcer. If other crops have to be cultivated, the feed source of the animals will change. The dairy production has to be adapted to the new or other feed stuffs available on the farm. The water will take on a new importance if it becomes scarcer and so an increase in water productivity had an influence on the economic success of the farm. Some farmers take part in landscape conservation programs or keep their animals in an extensive way and get paid for. Saving water is not in their focus, since the farms generate their income from the programs. The feed, which has its origin in landscape conservation programs, may not have the highest water productivity, but it has to be fed and if not, the water demand will remain. This "by-product" of landscape conservation has to be used by such other by-products like soy bean meal, rape seed meal or beet pulps silage. These products are available and it is a chance to use them to cover a part of the feed demand of the dairy cows and to convert these products into highly digestible food for humans.

4.4.3 Influence of the replacement rate on the water productivity of milk

Figure 6 shows the influence of the replacement rate on the water productivity of milk at different milk yields. The water productivity of milk decreases with an increase in the replacement rate. This was expected since the share of water input for the replacement on total water input increases. An increase in the replacement rate of 5 % decreases the WP_{milk} by 2.7 %. This effect was observed at all milk yields. 2,540 m^3 of water input is needed to rear a heifer with a diet including grazing in summer. A whole year confinement will need 30 m^3 more water. At a milk yield of 4,000 kg FCM cow^{-1} $year^{-1}$ and a replacement rate of 40 % the water input of the replacement is 0.26 m^3 kg^{-1} FCM, which is 28 % of total water input. At a milk yield of 12,000 kg FCM and the same replacement rate the water input is only 0.085 m^3 kg^{-1} FCM, which is 14 % of total water input. A specific WP_{milk}, such as 1.7 kg FCM m^{-3} water input, could be achieved with a milk yield of 6,000 kg FCM and a replacement rate of 10 %, 8,000 kg FCM and a replacement rate of 20 %, 10,000 kg FCM and a replacement rate of 30 % and 12,000 kg FCM and a replacement rate of 35 %. For economical and genetical reasons, a replacement rate of 10 % is not aspired too, since the genetic progress of the dairy herd would be lower. A replacement rate of 25 % is recommended by Weiher (2004) to get a high genetic progress with low replacement costs. The WP_{milk} at this replacement rate would be 0.1 kg FCM m^{-3} water input higher, than at the current replacement rate in Brandenburg, which is 15 % higher (LKV BB, 2014). Improving the water productivity of milk by decreasing the replacement rate is a possible way, but it is limited.

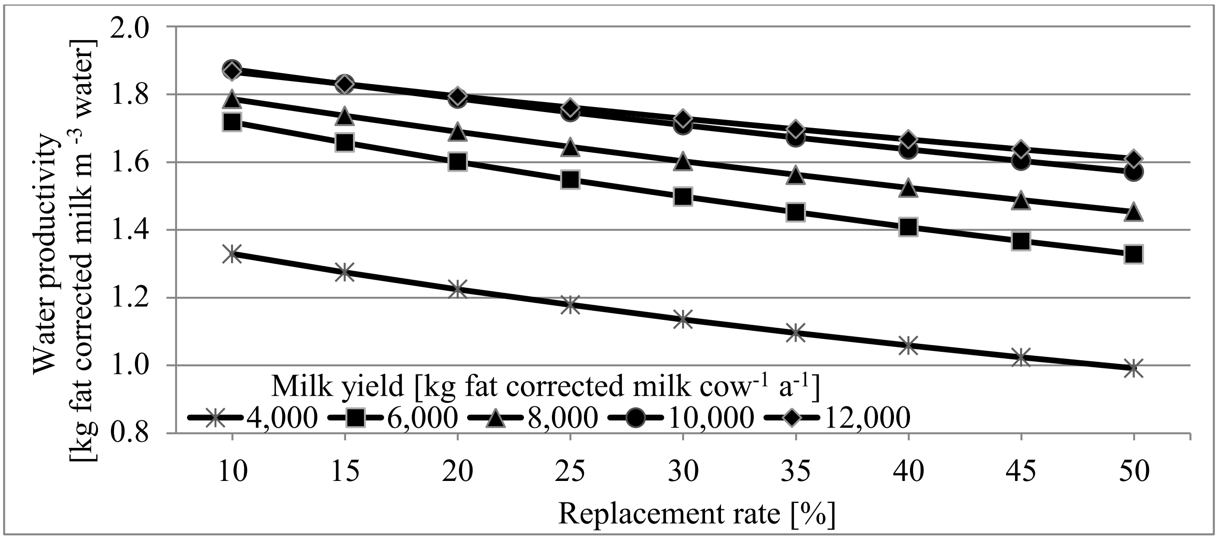

Figure 6: Influence of the replacement rate on the water productivity of milk

4.5 Conclusions

Management strategies to improve the water productivity of milk production under conditions in North-East Germany, such as varying milk yield, feeding strategies, and replacement rates, can be used alone or in combination. Among these management strategies, the milk yield has the strongest influence on the water productivity of milk production. Particularly an increase in milk yield from a low to an intermediate level leads to a pronounced increase in water productivity, while an increase from a high milk yield to a very high milk yield does not further increase water productivity. Increasing the milk yield up to 10,000 kg FCM per cow and year would be favorable in terms of water productivity. Diets affect water productivity as well. They should contain mostly roughage, such as grass silage, maize silage, and pasture, and only few concentrates. The influence of the replacement rate on water productivity is low. The actual replacement rate should not be further increased. The method applied here with regional data can be adopted on farm scale as well as to provide strategies for increasing the water productivity of milk in individual farms.

5 Drinking and cleaning water use in dairy farming

5.1 Preliminary remark

Chapter 5 is mainly based on Krauß et al. (2016), which is part of this thesis, and can be found in Annex C. More details are given there.

5.2 State of the art and subject-specific aims

The drinking water demand of dairy cows was investigated in several studies (e. g. Cardot et al., 2008; Holter and Urban, 1992; Meyer et al., 2004; Murphy et al., 1983). The investigations were made at early to mid-lactation and took at most 16 weeks. The end of the lactation is not well investigated. The studies used different methods and identified different influencing factors to estimate a regression function of drinking water demand of the cows. A wide range of the water demand is observed when the water demand is calculated with the different regression functions with the same input variables.

Scientific investigations of the cleaning water demand in a dairy cow barn are scarce (Palhares and Pezzopane, 2015). The cleaning water demand of a dairy cow barn is mostly investigated by public authorities and consulting agencies (e. g. Jensen, 2009; KTBL, 2008; Rasmussen and Pedersen, 2004; Schuiling et al., 2001; Steward and Rout, 2007; Williams, 2009). In most of the studies the estimation of the cleaning water demand is not described in detail or to reproduce the results. There are a lot of influencing factors, such as the cleaning system, management, constructional conditions, and size of the cleaned area and equipment, which make the results of the studies not comparable.

The aim of this study was to investigate the technical water use in a dairy cow barn on a commercial dairy farm in North-East Germany with respect to a detailed measurement of the drinking and cleaning water demand over two years. Regression functions of the drinking water demand over the whole lactation were developed and compared with existing regression functions and methods to test the equations for their accuracy. Two milking systems were compared with respect to technical water demand per cow, kg milk and milking. Diurnal and annual variations in the water demand were displayed for groups of cows with different milk yields. Detailed portioning of the cleaning water demand to the main contributors was outlined and recommendations to reduce the water use were given.

5.3 Materials and methods

5.3.1 Layout of the farm and the dairy cow barn

The investigated dairy farm is located in North-East Germany and manages 675 ha of arable land. The farm keeps on average 210 dairy cows and 180 calves and heifers. The dairy cow barn has a length of 70 m and a width of 30 m. An automatic milking system (AMS) with two single boxes and a 2x7 herringbone milking parlour (HBP) are established on the farm. The cows have free access to the AMS and so the milking frequency was nearly three milkings per day. In the HBP the cows were milked two times a day. Depending on the milk yield during the lactation phase and the milking intensity, the cows were changed between the milking systems or the groups during lactation. The cows were milked in the HBP the first two weeks after calving. Between the 15th day in milk and the 170th day in milk they were milked in the AMS. After the 170th day in milk, and up to the end of the lactation, the cows were milked in the HBP again. The milk yield was recorded at each milking for every cow in the AMS. The two single boxes of the AMS have an area of 35 m^2 and were cleaned with a hose. For the milk yield of the cows in the HBP, the data of the monthly milk performance testing was taken into account. The HBP has an area of 70 m^2 and was cleaned with a hose and a high-pressure cleaner. The milk was stored in two milk tanks and was collected by a milk truck every two days. The milk tanks were cleaned automatically after emptying.

5.3.2 Water metering

The water of the barn is supplied by a farm-owned well. On 23.02.2012 38 water meters (Itron Inc., USA) were installed at various points of water withdrawal. A ground plan of the barn and the installation points of the troughs are shown in Figure 7. The water withdrawal was measured in as much detail as the installation of the water pipes allowed over a period of more than two years, up to 08.05.2014. The drinking water intake of the cows and the cleaning water demand of the milk tank, the milking system, and the surface of the milking parlour were measured separately for each group. There was also unspecific withdrawal, which cannot be allocated to one of the milking systems, such as water used for cleaning the floor of the milk tank room, the milk cans and the workers' clothes. The water meters transmitted their count wirelessly to a collector every hour. The collector transmitted the counts daily to an access point and this transmitted the data to a file transfer protocol (FTP) server. The data of the FTP server was imported to the software Everblu (Itron Inc., USA). The data were controlled frequently in Everblu to check the data transfer and the counts of the water meter. The barn manager was called if the measured values were not in a normal range (such as continuously high water withdrawal during the night). An incident was recorded to identify these events in the statistical analyses. Complete datasets are available for 802 of the 806 days. Four datasets were excluded from the analyses because of missing values of the water meters. The measured drinking and cleaning water demand was compared with values of comparable studies. Outliers of the drinking water measurements were excluded if the values differed more than 1.96 x standard deviation for the mean value (Maidment, 1993).

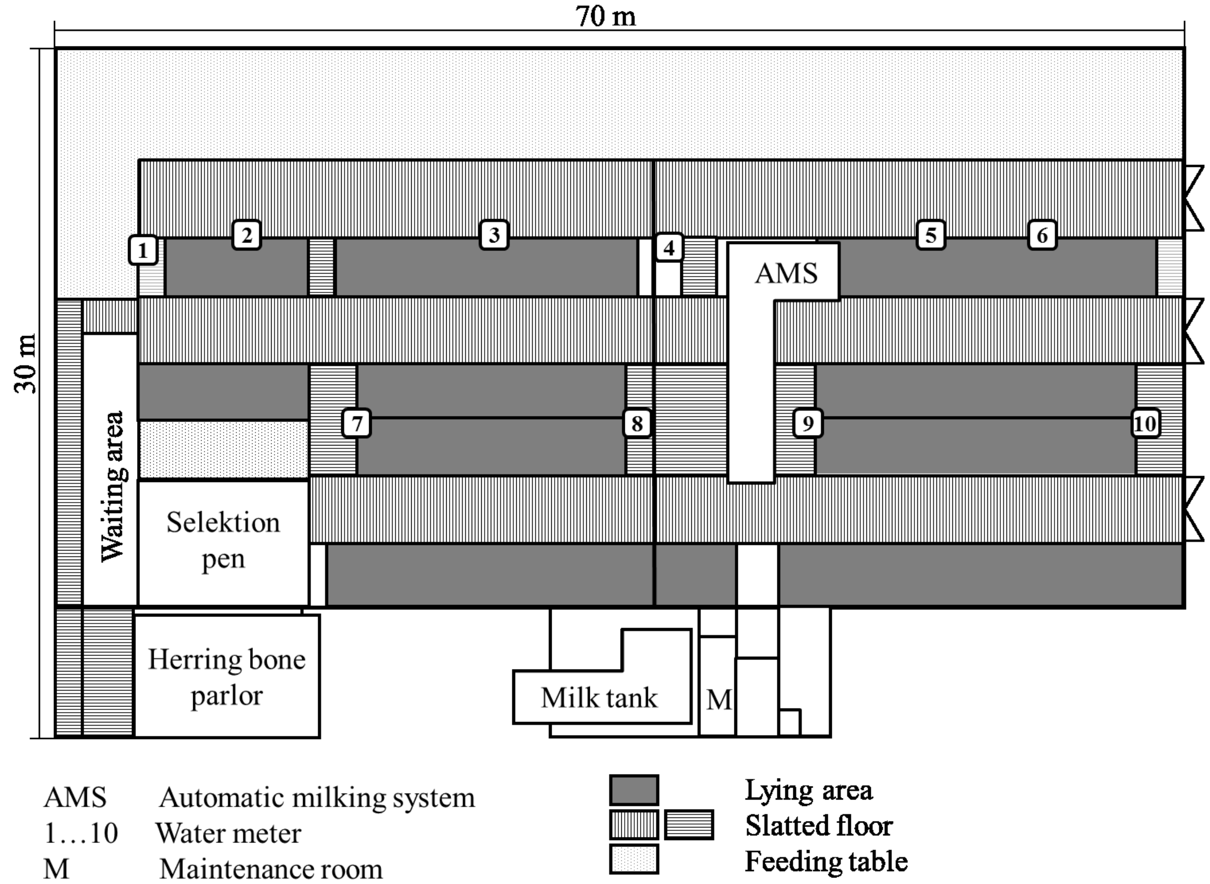

Figure 7: Plan of the dairy barn with milking systems and drinking troughs

5.4 Results and discussion

5.4.1 Drinking water demand

The daily drinking water intake per cow in the AMS and the HBP throughout the observation period is shown in Figure 8 and Figure 9. The 88 cows in the AMS group drink on average 8.0 m^3 of water per day. This is equivalent to 91.1 L water per cow and day or 2.6 L per kg milk. The mean drinking water demand of the cows in the HBP group is 54.4 L water per cow per day or 2.1 L per kg milk. The drinking water intake of the cows in the AMS showed a seasonal response. The highest amount of drinking water intake was observed in the summer with daily mean temperatures between 20 to 30 °C. The lowest water intake was observed in the winter with daily mean temperatures below 0 °C. The drinking water intake of the cows in the HBP did not show such a seasonal response. Cardot et al. (2008), Holter and Urban (1992), Meyer et al. (2004) and Murphy et al. (1983) also identified the drinking water intake as dependent on the temperature or season. These studies were made from early to mid-lactation, as for the cows in the AMS in this study, and so this influence could be reproduced and confirmed. The group of cows in the HBP is more heterogeneous than in the AMS and at the end of the lactation, so potentially the effects of temperature on drinking water intake could have been levelled out. It cannot be said if the seasonal independence of drinking water intake in the HBP is usual or not.

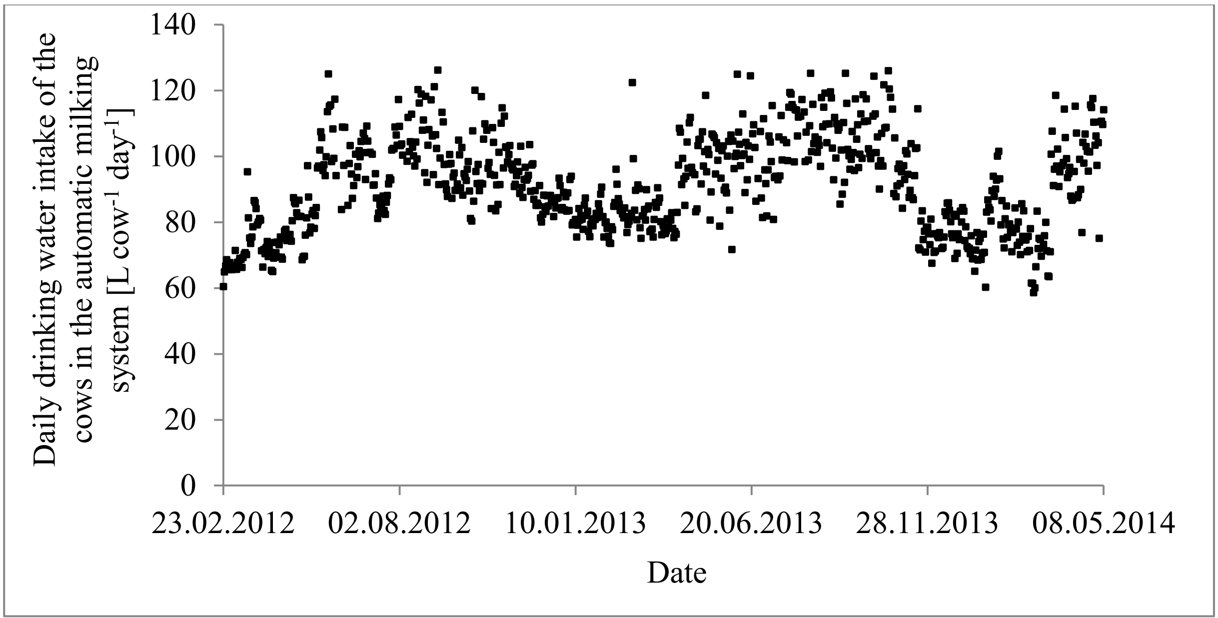

Figure 8: Daily drinking water intake per cow in the automatic milking system (AMS)

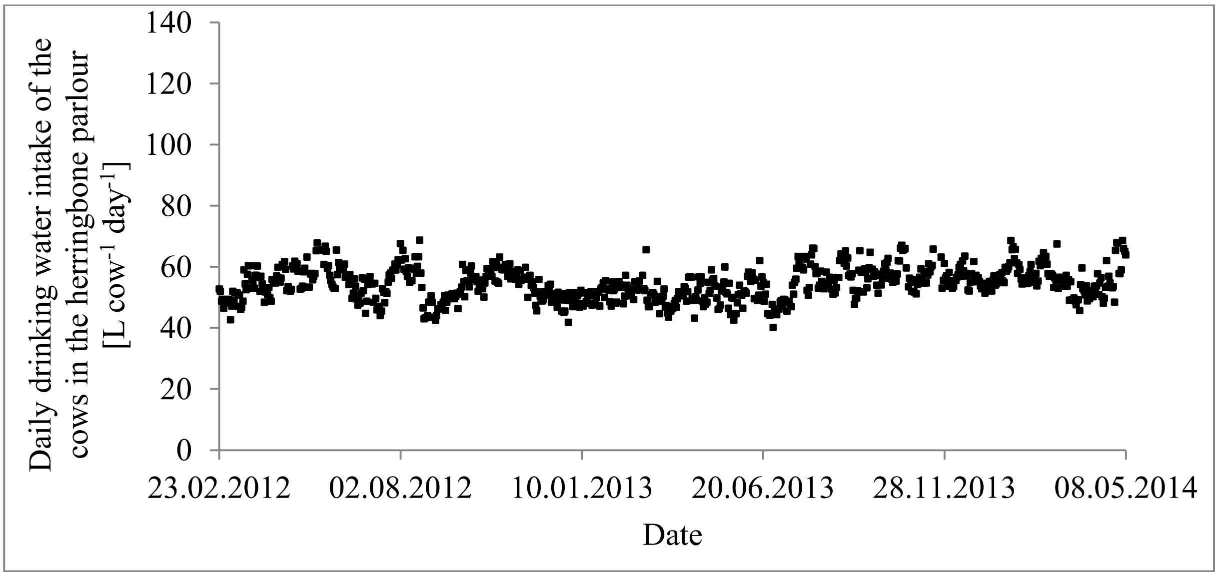

Figure 9: Daily drinking water intake per cow in the herringbone parlour (HBP)

The drinking water intake changes also during the day, as shown in Figure 10 and Figure 11. Between 6:00 and 19:00 h the cows drink nearly 70 % of their daily water intake and between 05:00 and 21:00 h 80 % of their daily water intake. This allocation was observed in both groups. During this time the workers are in the barn and it is lit. The peak of drinking water intake of the cows in the AMS is between 06:00 and 08:00 h. Till 18:00 h the drinking water intake varies only in a small range. The cows in the HBP drink most of the water between 06:00 and 08:00 h and between 16:00 and 18:00 h. This was expected, since the cows in the HBP were milked at these two times and cows drink large amounts of water after milking (Cardot et al., 2008). Since the cows in the AMS were milked continuously there is only one peak in drinking water intake.

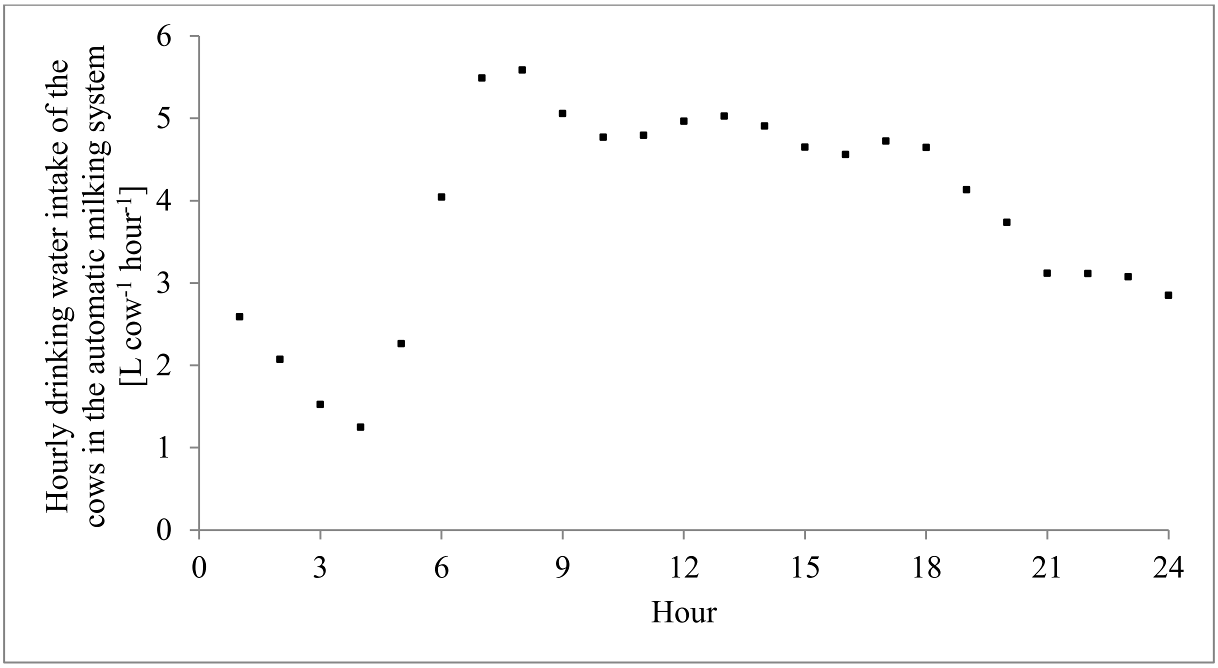

Figure 10: Hourly drinking water intake over the observation period in the automatic milking system (AMS)

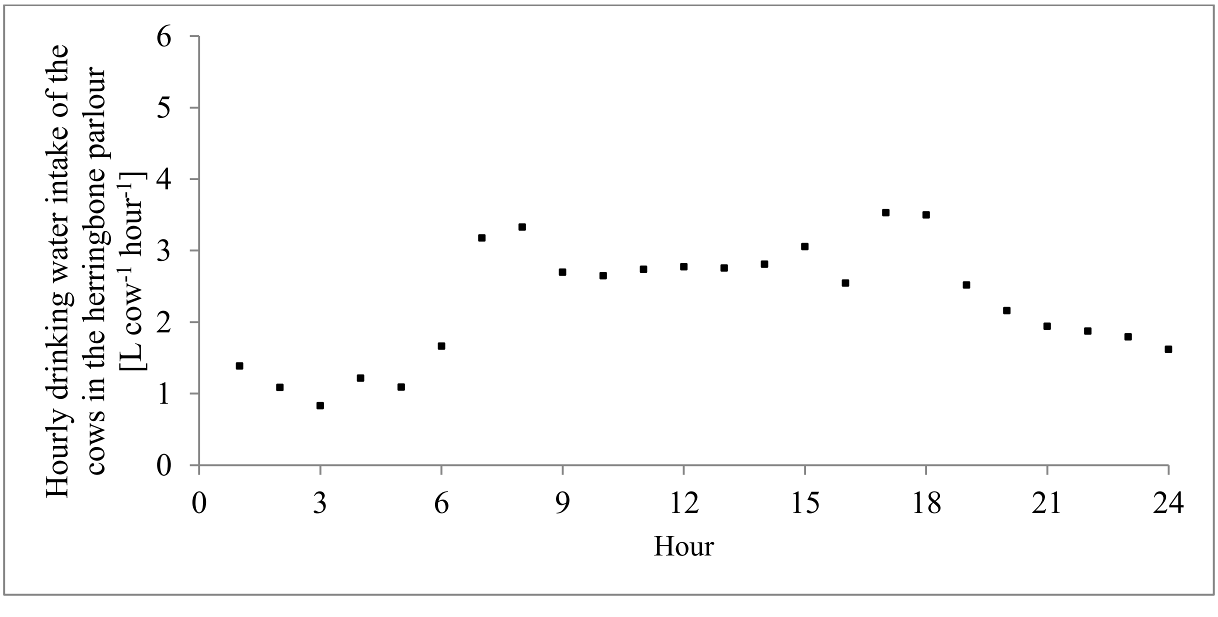

Figure 11: Hourly drinking water intake over the observation period in the herringbone parlour (HBP)

The investigated regression functions of Cardot et al. (2008), Holter and Urban (1992), Meyer et al. (2004), and Murphy et al. (1983) result in differences between the estimated and the measured daily drinking water demand. Not all parameters affecting the water intake of the cows were explained by the regression functions, since more parameters influencing water intake were investigated than were finally included in the regression functions. The above mentioned regression functions were developed for cows in early to mid-lactation. Further reasons for the difference between estimated and measured drinking water intake may be factors that were not investigated, such as e. g. rank fights, genetics, physiology, sexual cycle, behavior and disturbance caused by external factors.

The measured drinking water demand of the cows in the AMS and the HBP, the *milk yield of the cows* [kg cow^{-1} day^{-1}] and the *mean temperature* [°C] were used to develop a new regression function for estimating the drinking water demand:

$$\boldsymbol{W_{drink-cow\_daily} = -27.93 + 0.49 * mean\ temperature + 3.15 * milk\ yield} \quad (R^2 = 0.67)\ \mathbf{(1)}$$

This regression function includes only two parameters, since others such as live mass, dry matter intake or sodium intake were not measured in this commercial dairy herd. The coefficient and hence the influence of the milk yield on drinking water intake in this study is higher than in the other regression functions. This can be explained by the interdependence of the different parameters, for example a higher live mass of the cows is correlated with a higher feed intake capacity and a higher dry matter intake will lead to a higher milk yield. If the live mass and the dry matter intake are not included in the regression function, a part of its influence will be compensated by the milk yield parameter (Khelil-Arfa et al., 2012). Given a water demand between 600 and 700 L per kg milk for the production of feed, the measured water demand for drinking is 0.4 % of total water demand.

5.4.2 Cleaning water demand

The daily cleaning water demand of the AMS is shown in Figure 12 and of the HBP in Figure 13. The cleaning water demand is higher in the HBP than in the AMS. On average 2.5 m^3 water is used per day to clean the AMS, which is 28.6 L per cow and day or 0.8 L water per kg milk. Over 3 m^3 water is used per day to clean the HBP, which is 33.8 L water per cow and day or 1.3 L per kg milk. The HBP needs 18 % more water than the AMS. The daily cleaning water demand ranged from 1.1 m^3 to 18.1 m^3 in the AMS and from 1.1 m^3 to 15.2 m^3 in the HBP. In the AMS 80 % of the values were between 1.5 m^3 and 3 m^3 and 90 % between 1.5 m^3 and 4 m^3. In the HBP 60 % of the values were between 1.5 m^3 and 3 m^3 and 85 % between 1.5 m^3 and 4 m^3.

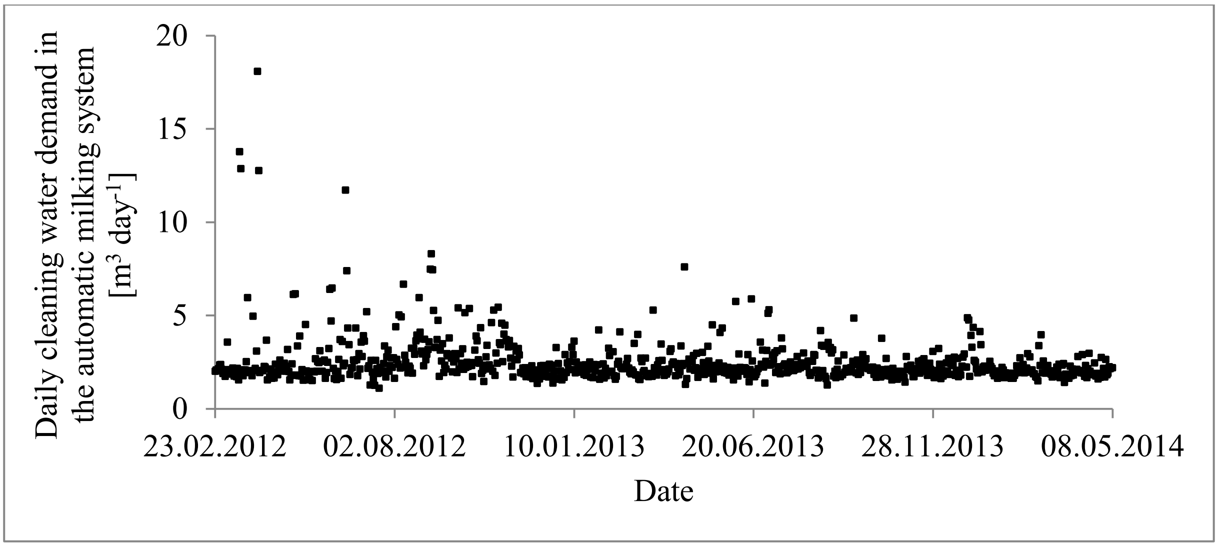

Figure 12: Daily cleaning water demand in the automatic milking system (AMS)

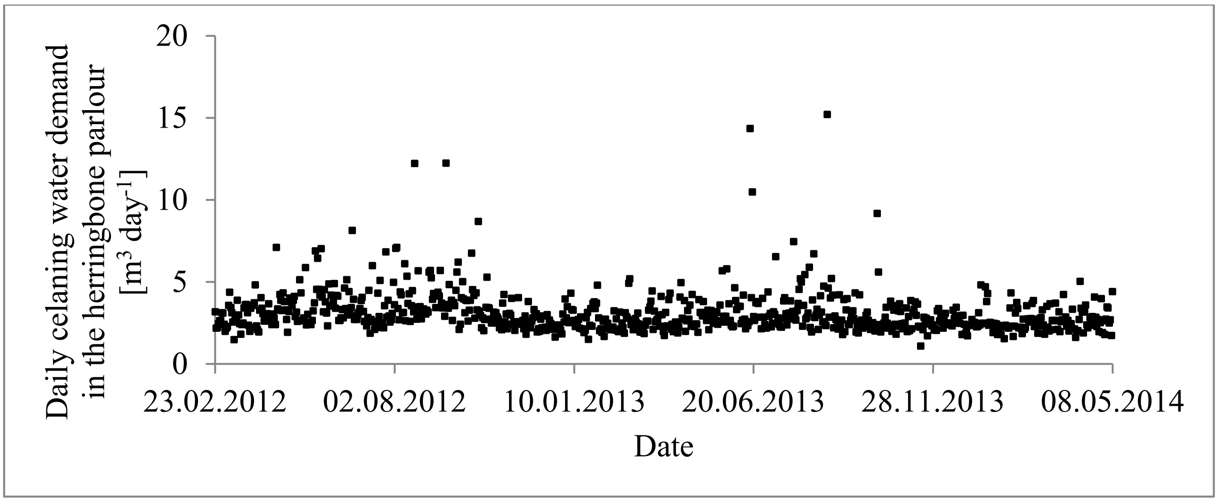

Figure 13: Daily cleaning water demand in herringbone parlour (HBP)

The high cleaning water use in the HBP is caused by the cleaning system and the fact that there is no incentive to save water. Influences on the cleaning water demand and the high variability may be also the structural design of the milking parlour, the pre- and post-waiting areas, the cleaning technology, the applied water pressure, but also operationally defined cleaning routines (Pommer et al., 2013).

In the AMS the share of drinking water demand is 76 % and the share of cleaning water 24 % of the total technical water demand. This is comparable with the results of Drastig et al. (2010). In the HBP, 62 % of the water is needed for drinking and 38 % for cleaning. The difference is explained by the higher cleaning water demand per cow and the lower drinking water demand per cow in the HBP.

It is difficult to make general statements about reductions of the technical water demand in a dairy barn, since the water demand of drinking and cleaning has a high variability. The measured demand on a commercial farm is higher with a higher variability than expected with using values of the literature (Pommer et al., 2013). Drinking water has to be provided in accordance with the demand of the cows. Reductions can be made as described in section 4 by a lower share of the demand for maintenance on the total demand. Cleaning of the milking system was computer-controlled and so there are limited technical boundaries to reduce the water demand. The water demand of cleaning the parlour can be reduced by educating the workers to reduce water use, by using high-pressure cleaners or mechanical cleaning methods such as a brush or by optimized structural design. The cleaning water demand per liter of milk could be reduced with more milk milked per cleaning cycle if the total cleaning water demand cannot be reduced. Given a water demand between 600 and 700 L per kg milk for the production of feed, the measured water demand for cleaning the barn is 0.1 % of total water demand for the AMS and 0.2 % for the HBP.

5.5 Conclusions

The milking system, the management, environmental factors and the milk yield are the main influencing factors on the technical water demand of the dairy farm. The drinking water intake is influenced by the ambient temperature and the milk yield. The automatic milking system has a lower cleaning water demand per cow and day than the herringbone parlour. The technical water demand in the barn has a negligible contribution to the total water demand in dairy farming since the major water demand is for feed production.

6 Water productivity of poultry production: The influence of different broiler fattening systems

6.1 Preliminary remark

Chapter 6 is mainly based on Krauß et al. (2015b), which is part of this thesis and can be found in Annex B. More details are given there.

6.2 State of the art and subject-specific aims

The world poultry production will increase by 1.9 % per year and will be the world largest meat sector in 2022 (OECD, 2013). Poultry meat is acceptable by all major religious and cultural groups (Steinfeld et al., 2006). The poultry production in Germany increased from 0.9 million tons in 2003 to 1.5 million tons in 2014 (German Federal Statistical Office, 2013;

German Federal Statistical Office, 2014). In 2014, 1.0 million tons or 64 % were accounted by broiler meat. In 2005 the share of broiler meat on total poultry meat production was only 55 % (German Federal Statistical Office, 2014). The main focus of studies about water use in livestock production was on milk and beef production. Studies on the water productivity of poultry are scarce (Chapagain and Hoekstra, 2003; Drastig et al., 2016; Renault and Wallander, 2000). The water productivity of poultry has a wide range caused by different regions investigated and with the climate conditions and predominant keeping conditions. As described above, the water demand for feed is expected to be the largest contributor to total water demand (Peden et al., 2007; Singh et al., 2003). Broiler chickens have a higher feed conversion ratio than cattle or swine. The pressure on resources could be reduced if people would eat less meat and the meat consumption would include more poultry.

The aim of this section was to quantify the water productivity of poultry production under commercial conditions in Germany and to investigate the influence of different broiler fattening systems. A highly water-productive poultry production system is outlined.

6.3 Materials and methods

6.3.1 System boundaries and data

The water productivity of poultry production was analyzed from cradle-to-farm-gate, including the broiler chicken and the parent stock. The water demand of feed supply, drinking and cleaning was considered here. The indirect water demand of the barn and the equipment was not considered, since it was assumed to be negligible, as is reported for milk production (de Boer et al., 2013; Döring et al., 2013).

The most common production systems in Germany according to the German Agricultural Society (Berk, 2008) were investigated. Diets were developed according to Jeroch et al. (1999). The data of water productivity of the feed were taken from Krauß et al. (2015a).

6.3.2 Fattening systems

The most common broiler fattening systems in Germany according to Berk (2008) were investigated (Table 2). A barn size of 1,700 m^2 was considered for the broiler chicken and the parent stock. In the barn of the parent stock 8,500 hens and 850 cocks were kept. 150 broiler chickens were generated per hen in 64 weeks (Jiang et al., 1998).

Table 2: Broiler fattening systems according to Berk (2008)

Fattening system	Animals per barn[a]	Fattening period [d]	Final mass [kg]	Carcass mass [kg]	Feed conversion ratio [kg live mass kg^{-1} feed]
Fast fattening	39,900	30	1.6	1.1	0.625
Intermediate fattening	31,000	37	2.1	1.5	0.581
Splitting fattening total	39,900				
- Young[b]	8,900	30	1.6	1.1	0.625
- Old[b]	31,000	37	2.1	1.5	0.581
Slow fattening total	31,000				
- Female young[b]	9,300	39	2.0	1.4	0.556
- Female old[b]	6,200	46	2.3	1.6	0.556
- Male	15,500	46	3.0	2.1	0.556

[a] barn size of 1,700m²

[b] 7 days difference in age of slaughtering between the young and the old animals

6.3.3 Composition and intake of feed

The feed of the broiler chicken contained maize grain, rapeseed meal, rapeseed oil, soy bean meal, winter barley and winter wheat. Three diets were developed according to Jeroch et al. (1999) to cover the demand of maintenance and yield. All diets contained 5 % rapeseed oil. The broiler chicken at the fast fattening, the intermediate fattening and the splitting fattening get a protein rich feed with 4 % rapeseed meal, 39 % soy bean meal and 52 % grain over the whole fattening period. The broiler chicken in the slow fattening gets this feed the first 25 days. Till the end of the fattening period the broiler chicken get a grain rich feed with 67 % grain, 23 % soy bean meal and 5 % rape seed meal. The parent stock gets a feed with 85 % grain and 10 % soy bean meal. The feed intake was calculated according to the final mass and the feed conversion ratio shown in Table 2. A feed intake of 400 g per broiler chicken was assumed for the parent stock (Jiang et al., 1998).

6.3.4 Calculation of the water productivity

The water productivity of broiler chicken was defined as the relation of the output (on mass basis, food energy basis and food protein basis) to the water input. The mass output was defined as the carcass mass of the broiler chicken (kg_{cm}).

The water productivity of the diets was calculated, as described above for the dairy cows, by multiplying the share of the feed components in the diet by the water productivity of the components. The water productivity of the poultry meat $WP_{poultry\text{-}meat}$ (kg_{cm} m^{-3} W_{input}) was defined by the carcass mass per broiler chicken related to the water input W_{input} (m^3). The water productivity of the food energy and food protein of poultry meat $WP_{poultry\text{-}energy}$ (MJ m^{-3} W_{input}) and $WP_{poultry\text{-}protein}$ ($g_{protein}$ m^{-3} W_{input}) was defined by the food energy and food protein produced per broiler chicken related to the water input W_{input} [m^3]. The food energy content of the carcass was calculated according to USDA (2013) with 8.92 MJ kg_{cm}^{-1} and the food protein content with 183.3 g kg_{cm}^{-1}.

The water input of poultry production W_{input} (m^3) includes the transpiration from precipitation, irrigation water, drinking and process water in the barn and indirect water.

The water input consists of the water input of feed production $W_{input-feed}$ (m^3), the water used in the barn, which is provided by technical means, $W_{tech-barn}$ (m^3), and the water needed for replacement of the broiler chicken $W_{input-parent}$ (m^3). $W_{input-parent}$ is part of the indirect water demand.

The water input of the feed is the sum of crop transpiration from precipitation $W_{prec-transp}$ and the irrigation water W_{irri}. The technical water in the barn is the sum of the cleaning water demand and the drinking water intake of the animals. The water input of the parent stock is the sum of the water input of the feed and the technical water demand in the parent barn.

The water demand of feed production was calculated as described for the dairy cows in section 4.3.2.

The technical water demand in the barn includes the drinking water intake of the broiler chicken and the cleaning water demand of the barn, the hygiene lock and the washing machine ($W_{input-clean}$). The cumulative drinking water demand per broiler chicken $W_{input-drink-broiler}$ (m^3) was calculated according to KTBL (2009) as a function of age in weeks *x*:

$$\mathbf{W}_{\boldsymbol{input-drink-broiler}} = \mathbf{0.00042}\, \boldsymbol{x}^{\mathbf{1{,}623}} \quad [m^3] \tag{2}$$

The drinking water demand of the parent stock was considered at 0.3 L day^{-1} $animal^{-1}$ (KTBL, 2009).

The cleaning water demand of the barn includes water for soaking, cleaning and disinfection and ads up to 24.4 L m^{-2} (KTBL, 2009). The water demand for hygiene lock and the washing machine for the work-wear was 50 L day^{-1} (KTBL, 2009).

6.4 Results and discussion

The water productivity of the feed components is shown in Table 3. The WP_{feed} of the protein-rich feed of the broiler chicken in the fast fattening is 0.7 kg dry matter m^{-3} water input. The grain-rich feed of the broiler chicken in the second phase of the slow fattening has a WP_{feed} of 0.8 kg dry matter per m^3 water input. The lower water productivity of the protein-rich feed was expected, since the protein-rich components had lower water productivity than the grain. This effect was observed also in the diets of the dairy cows. The feed of the parent stock has a water productivity of 1.0 kg dry matter m^{-3} water input.

Table 3: Water productivity of the feed components

Component of the diet	Water productivity in kg DM[a] m^{-3} $W_{input\text{-}feed}$	Standard deviation
Maize grain	1.8	±0.3
Soybean meal[b]	0.4	
Winter barley	1.3	±0.3
Winter rapeseed meal	0.8	±0.2
Winter wheat	1.1	±0.2

[a] DM= dry matter

[b] according to Prochnow et al. 2012

The water input, product output and water productivity of the fattening systems are shown in **Table 4**. The water input of the parent stock is 0.365 m^3 per broiler chicken. An additional liter of water is needed per broiler chicken to cover the demand of the parent stock for drinking and cleaning the barn. Per broiler chicken the water input of the parent stock is 0.366 m^3 water. The water input of the feed increases with an increasing fattening period. The broiler chicken in the fast fattening had a water input of 3.2 m^3 water, while a male in the slow fattening system needs nearly twice the water for feed production. However, the males in the slow fattening system reach a carcass mass which is twice as high. The total water input of the fast fattening was the lowest of all investigated systems. The water input of the intermediate fattening is 5 % and of slow fattening 20 % higher. The splitting fattening, as a combination of intermediate fattening and fast fattening has the highest water input with 181,780 m^3. The water input of feed production accounts for 90 to 93 %, the water input of the parent stock for 7 to 10 % and the water input of drinking and cleaning for less than 1 % of the total water input. The water input of the parent stock results from more than 99 % of the water of the feed production.

Table 4: Water input, product output and water productivity of the fattening systems

		Fattening system									
		Fast fattening	Intermediate fattening	Splitting fattening			Slow fattening				Parent[b]
				Young[a]	Old[a]	Total	Female young[a]	Female old[a]	Male	Total	
Water input											
$W_{input-feed}$	m^3 $broiler^{-1}$	3.2	4.5	3.2	4.5		4.2	4.7	6.0		0.365
$W_{input-drink}$	m^3 $broiler^{-1}$	0.004	0.006	0.004	0.006		0.007	0.009	0.009		0.001
$W_{input-parent}$	m^3 $broiler^{-1}$	0.366	0.366	0.366	0.366		0.366	0.366	0.366		
$W_{input-feed}$	m^3 $barn^{-1}$	128,509	138,246	28,665	138,246	166,911	38,637	29,007	93,636	161,279	464,933
$W_{input-drink}$	m^3 $barn^{-1}$	178	194	40	194	234	63	55	138	257	1,382
$W_{input-clean}$	m^3 $barn^{-1}$	44	44			44				44	65
total W_{input}	m^3 $barn^{-1}$	143,322	149,821			181,780				172,918	466,380
Output											
Animals per barn		39,900	31,000	8,900	31,000	39,900	9,300	6,200	15,500	31,000	9,350
Carcass mass	kg $broiler^{-1}$	1.1	1.5	1.1	1.5		1.4	1.6	2.1		
Mass output	kg_{cm}[c] $barn^{-1}$	44,688	45,570			55,538				55,552	
Food energy content	MJ kg_{cm}^{-1}	8.92	8.92			8.92				8.92	
Food energy output	MJ $barn^{-1}$	398,617	406,484			495,399				495,524	
Food protein content	$g_{protein}$ kg_{cm}^{-1}	183.3	183.3			183.3				183.3	
Food protein output	kg $barn^{-1}$	8,191	8,353			10,180				10,183	
Water productivity											
$WP_{poultry-meat}$	kg_{cm} m^{-3} W_{input}	0.3	0.3			0.3				0.3	
$WP_{poultry-energy}$	MJ m^{-3} W_{input}	2.8	2.7			2.7				2.9	
$WP_{poultry-protein}$	$g_{protein}$ m^{-3} W_{input}	57	56			56				59	

[a] 7 days difference in age of slaughtering between the young and the old animals (see Table 2)

[b] The values per broiler represent the water input per broiler chicken. The values per barn represent the water input of the parent barn.

[c] cm= carcass mass

The mass output of the fast and the intermediate fattening is nearly 45 t carcass mass per barn. The mass output of the splitting and the slow fattening is 10 t per barn higher. Since the food-energy and food-protein content of the carcass is determined to be equal between the fattening systems, the food-energy and food-protein output show the same relation as the mass output.

The water productivity of the poultry meat was estimated at 0.3 kg carcass mass per m^3 water input and is equal in all fattening systems. The water productivity of food-energy and food-protein is also nearly the same between all systems, with the highest in the slow fattening and the lowest in the intermediate and splitting fattening. The higher water input of the splitting and slow fattening was compensated by a higher output. In the fast fattening the broiler chicken were fed only with protein-rich feed, which has lower water productivity than the grain-rich feed of the broiler chicken in the slow fattening. The positive effect of a higher feed conversion ratio was compensated. The effect of different diet compositions on the water productivity was observed as described for the dairy cows. All investigated fattening systems were intensive in the point of daily gain and feed conversion ratio. More extensive systems may have the same product output by a longer fattening duration and a lower feed conversion ratio. The higher water productivity of the feed may compensate for a part of the higher feed intake. The water input of the feed is the major contributor to the total water input. This was expected since it was described in the literature (Peden et al., 2007; Singh et al., 2003) and observed by investigating the water productivity of milk. The water productivity of poultry meat will be influenced by improving the water productivity of the diet components. This could be achieved by an adjustment in plant production, by replacing components of the diets with low water productivity, such as wheat, with more water productive diet components, such as maize for grain. Another way is to use free amino acids, which were produced industrially.

6.5 Conclusions

Feed production accounts for the major share of the water input in poultry production. The water productivity in poultry production is not affected by the intensity of the broiler fattening system. Higher water input is compensated by a higher output of mass, food energy, and food protein in slower fattening systems compared with the fast fattening system.

7 Overall discussion

The investigations have shown the major influence of the feed production on the water productivity of animal products such as milk and poultry meat. This has also been described in the literature (e. g. de Boer et al., 2013; Drastig et al., 2016; Peden et al., 2007; Singh et al., 2003). An increase in the water productivity of livestock farming could be achieved with an increase in the water productivity of the feed production. In this study the water productivity of feed production in Brandenburg was investigated. Within this part of North-East Germany the water productivity of feed varied widely between the agricultural growing regions and the different feedstuffs. The variation would be even higher when investigating a larger region as described by, e. g. Molden et al. (2010) and Sultana et al. (2015). Not all crops can be cultivated in the whole region. The availability of feed components depends on the region. But even in one region the crop management will differ between farms, so there will not be one preferable solution to feed the animals for a high water productivity of animal products (Murphy et al., 2016). Overall recommendations on feed and animal production will show a direction for improving the water productivity. A farm scale modelling is needed to advise a farm manager in terms of increasing the water productivity. The recommendations have to fit into the operational concept of the farm. Economics, site, crop rotation, technology and infrastructure, such as planting, harvesting, processing and storage, may play a prior role in management decisions to increase the water productivity, which was also described for farms in Ethiopia (Kebebe et al., 2015).

The diets of the animals were developed according to recommendations in the literature in terms of energy and protein content and the use of specific components (Jeroch et al., 1999; Kirchgeßner, 2004; Kraatz, 2012; Spiekers and Potthast, 2004). The components used in the diets were producible in Brandenburg or can be easily imported, such as soy bean meal. The development of the diets was completed before the water productivity of the feedstuffs was known, so an improvement to a most water productive management strategy was not possible. On the farm the water productivity of the feed is known before the diets were developed. An increased use of water productive feedstuffs can be achieved. This optimization is restricted to some points of animal nutrition, such as: taste, feed intake, anti-nutritive ingredients, swelling power, amino acid pattern, structure, degradability and degradation rate (Halachmi et al., 2015).

An increase in yield of the dairy cows leads to an increase in WP_{milk}. This effect diminishes at a milk yield of 10,000 kg FCM cow^{-1} $year^{-1}$. A further increase in milk yield does not increase the water productivity of milk anymore. An increase in the intensity of broiler production does not lead to an increase in water productivity, so a further intensification of production will not lead to a better water productivity. A case study of Brazilian broiler production shows also only slight differences in the water productivity of different farms (Drastig et al., 2016).

The water input of the replacement of dairy cows has a share on total water input of 10 to 30 %. With a decreasing replacement rate the water productivity will increase. The current average replacement rate in Brandenburg is 40 to 45 %. A replacement rate of 25 % is recommended by Weiher (2004) to get a high genetic progress with low replacement costs. Improvements in water productivity can be made with a decrease of the replacement rate to the recommended rate. In broiler chicken production the water input of the parents on total water input is 7 to 10 %. Intensification in the parent stock will have less effect on the water productivity than an improvement in the replacement rate of the dairy cows.

The milking system has an influence on the water productivity of milk. The investigated herringbone parlour needs 18 % more cleaning water than the automatic milking system. Robinson et al. (2016) estimated a higher water demand of the AMS. Both milking systems may not be run with the maximum number of cows they could handle and where not optimized to a low water demand. The large surface of the herringbone parlour and the manual cleaning leads to a high water demand. Saving water is not the intention of the farm management and the workers, since the water is needed to keep the slurry pumpable.

The available regression functions on estimating the drinking water demand over- or underestimate the daily drinking water intake of the dairy cows. As described above, the drinking water intake of the animals depends on many influencing parameters. A regression function could not cover all these effects. Overall, it is not suitable to reduce the drinking water intake of the cows to save water, since animals have to have water all the time in an adequate quality and quantity (TierSchNutztV, 2006). A sufficient intake of drinking water will secure the wellbeing and the yield of the animals. The regression functions can be used to check the drinking water intake and to detect weak points of the water supply.

Beside the production of food and feed and to maintaining the cultural landscape, farms have to exist in an economic environment. Water can enter the farm via precipitation, surface or subsurface flows, pre chains, irrigation or as tap water. All of this water has to have been paid for with a specific price: The precipitation by the access to land, surface or subsurface flows by a water right, the water bound in the pre chains by the products, the irrigation water by the water right and the pumps and the equipment to run them and the tap water by the pumps and the equipment to extract it or to the public water network operator. It depends on the price of the water if a farm manager wants to reduce the water use or not (Drastig et al., 2016). A decrease in technical water use will affect the water productivity in a minor way because the crop transpiration from precipitation has the greatest share on water input.

8 Overall conclusions and outlook

Feed production accounts for the major share of the water input in dairy and poultry production. The technical water has a minor contribution on the total water demand. An increase in water productivity of milk could be achieved with different management strategies, such as varying the milk yield, feeding strategies and the replacement rate. The milking system, the management, environmental factors and the milk yield are the main influencing factors on the technical water demand of the dairy farm. Varying the milk yield has the greatest influence on the water productivity of milk. A feeding strategy with a large share of roughage in the diet, such as grass silage, maize silage and pasture, shows the highest water productivity. The effect of the replacement rate on the water productivity is limited. The water productivity in poultry production is not affected by the intensity of the broiler fattening system.

Livestock diets should contain components with high water productivity with respect to availability, economics, and physiological regimentations. The use of free amino acids can optimize the amino acid pattern of the feed of non-ruminants. Other animal products should be investigated, such as the meat of dairy cows, Holstein-Friesian bulls and beef cattle, or pork, as recommendations for a water-productive human nutrition with animal products. The increase in water productivity should be regarded in terms of consumer request for more extensive keeping conditions, to regulations in legislation, and to the conservation of the cultural landscape.

9 Zusammenfassung

Die Wasserproduktivität in der Tierhaltung ist von vielen Faktoren abhängig. Die Futterproduktion hat den größten Anteil am Wasserbedarf von tierischen Produkten. Weitere Einflussfaktoren sind die Leistung, die Reproduktion und der Gesundheitsstatus der Tiere, das Management und die Haltungsbedingungen. In dieser Arbeit sollte untersucht werden, wie sich diese Faktoren auf die Wasserproduktivität von Milch und Geflügelfleisch in Nord-Ost-Deutschland auswirken. Zehn unterschiedliche Futtermittel wurden hinsichtlich ihres Wasserbedarfes untersucht. Aus diesen Futtermitteln wurden die Rationen bzw. das Mischfutter für die Tiere erstellt. Die Milchleistung der Kühe wurde zwischen 4.000 und 12.000 kg Milch pro Kuh und Jahr in 2.000 kg Schritten variiert, um den Effekt der Leistungssteigerung auf die Wasserproduktivität zu untersuchen. Für jedes Leistungsniveau wurden zwölf verschiedene Fütterungsstrategien untersucht, welche auf der Erhöhung einzelner Bestandteile der Ration basieren. Der Wasserbedarf von Leitungswasser im Stall wurde mit 38 Wasserzählern ermittelt. Für die Wasserproduktivität des Geflügelfleisches wurden vier verschieden intensive Mastverfahren untersucht.

Die Wasserproduktivität steigt mit steigender Milchleistung der Kühe. Das Maximum wird bei 10.000 kg Milch pro Kuh und Jahr erreicht. Eine weitere Steigerung bringt keine Erhöhung der Wasserproduktivität mehr mit sich. Hinsichtlich der Fütterung zeigen Rationen mit einem hohem Gras- bzw. Maissilageanteil die höchste Wasserproduktivität.

Die Kühe, die im automatischen Melksystem gemolken wurden, nahmen mehr Tränkwasser zu sich, als die Kühe im Fischgrätenmelkstand. Dies ist durch die höhere Milchleistung bedingt, da andere Faktoren, wie Lebendmasse und Temperatur als vergleichbar angesehen wurden. Das meiste Tränkwasser wurde aufgenommen, wenn es im Stall hell ist. Im automatischen Melksystem wurden im Mittel 28,6 Liter Reinigungswasser pro Kuh und Tag benötigt. Für die Reinigung des Fischgrätenmelkstandes wurden 33,8 Liter pro Kuh und Tag genutzt.

Die untersuchten Broilermastverfahren zeigten keine Unterschiede hinsichtlich der Wasserproduktivität. Die intensivere Aufzucht und bessere Futterverwertung wurde durch eine niedrigere Wasserproduktivität des Futters kompensiert.

Der Anteil des technischen Wassers macht in der Milchkuh- und Broilerhaltung nur einen kleinen Teil am Gesamtwasserbedarf aus.

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12 Annexes

Annex A: Krauß, M.; Kraatz, S.; Drastig, K.; Prochnow, A. (2015a): The influence of dairy management strategies on water productivity in dairy farming. Agricultural Water Management 147, 175-186.

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The influence of dairy management strategies on water productivity of milk production

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ABSTRACT

Livestock production is the main user of water resources in agricultural production. The objective of this study is to quantify the effects of dairy management strategies such as feeding strategies, milk yield and replacement rate on the water productivity of milk. The study is based on site conditions of North-East Germany. The water input is considered as the sum of crop transpiration from precipitation, the total irrigation water and the drinking water of the animals. Four feeding strategies, based on the maximization of grass silage, maize silage, pasture and concentrate, were analyzed. The milk yield varied between 4000 and 12,000 kg fat corrected milk (FCM) cow^{-1} year^{-1} in steps of 2000 kg. Feed water productivity on a dry mass (DM) base varied widely between 1.5 kg(DM) m^{-3} of water input for grass silage and 2.6 kg(DM) m^{-3} for maize silage, 0.8–1.8 kg(DM) m^{-3} for grain and 0.4 kg(DM) m^{-3} for soybeans from Brazil. The water productivity of milk increased with an increasing milk yield. The lowest water productivity was calculated at 4000 kg(FCM) with 1.1 kg(FCM) m^{-3} water input. At a milk yield of 8000 kg(FCM) the water productivity was 1.5 kg(FCM) m^{-3} and at 10,000 and 12,000 kg(FCM) it was 1.6 kg(FCM) m^{-3}. The most beneficial conditions related to water productivity in dairy farming exemplarily for site conditions of North-East Germany are found to be with a milk yield about 10,000 kg(FCM) and a grass silage and maize silage based feeding.

1. Introduction

The increase of the world population to 10 billion people in 2050 (Lutz et al., 1997) and the change in human diets, to include more animal products (Delgado, 2003), will lead to an increasing food demand by 70–90% in 2050 (Rosegrant and Cline, 2003). There will be a competition for water among agricultural, domestic and industrial uses (Postel, 2000). Agricultural practices have to be improved to increase the efficient use of natural resources such as water, in order to meet the challenges of global change. Water is a major resource in agricultural production. In livestock operations, water plays a role as drinking water for the animals as well as in the feed production. Dairy farming is the most complex type of livestock operation (Descheemaeker et al., 2010; Kraatz, 2012), since it includes the production of feed, milk and meat.

Generally, water productivity is defined as the relation of output to water input (Bouman, 2007). However, the details of the calculations of water productivity can vary from study to study. In order to make comparison of results possible, Bessembinder et al. (2005) suggested that the method for determining output and water input be described meticulously. The output can be the product in dry or fresh weight or in an economic value (Bessembinder et al., 2005). The output can also be on a feed energy, feed protein, food energy or food protein base (Renault and Wallander, 2000). Beside the concept of crop water productivity (Bouman, 2007; Bouman and Tuong, 2001) a concept of livestock water productivity was developed (Peden et al., 2007). This concept uses the net livestock-related benefits as output of the system (e.g. Cook et al., 2009; Descheemaeker et al., 2010; Peden et al., 2009). The water input has to be described precisely as well, which includes the transpiration, the evapotranspiration, the irrigation water, etc. (Bessembinder et al., 2005). An increase in water productivity means that an increased amount of products and services are produced with the same amount of water or that the same amount of products are produced with less water (e.g. Bossio et al., 2010; Molden and Sakthivadivel, 1999; Renault and Wallander, 2000). Perry (1999) sees the concept of water productivity with more "crop-per-drop" as "the most important performance indicator in

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many countries", while Zoebl (2006) proposes that it is not the only meaningful indicator of agricultural production. For a comprehensive recent discussion of the water productivity concept see Pereira et al. (2012).

The regional focus of the investigations analyzing options to improve water productivity of livestock production was in Africa (e.g., Descheemaeker et al., 2010; Haileslassie et al., 2009; Rockström et al., 2010), Asia (e.g., Haileslassie et al., 2011; Singh et al., 2006) and Oceania (e.g., Armstrong et al., 2000; Moore et al., 2011; Zonderland-Thomassen and Ledgard, 2012). For Western Europe a case study on water productivity in dairy farming is available (Prochnow et al., 2012).

Several options have been reported to increase water productivity in dairy farming. An increasing performance of the cows can improve water productivity at Ethiopian conditions, since the share of maintenance related to the performance is reduced (Peden et al., 2009). An increasing share of crop residues and by-products in the diets can also increase the livestock water productivity (Descheemaeker et al., 2010). Diets should contain high digestible components and the nutrient composition has to be near the demand of the animals (Blümmel et al., 2009). Haileslassie et al. (2011) describe an increasing water productivity in the Indo-Ganga basin with intensifying the milk production up to 2000 l cow^{-1} year^{-1}. For Australian conditions a milk yield of 5350 kg cow^{-1} year^{-1} showed a higher water productivity than a 1500 kg lower milk yield (Armstrong et al., 2000). This was caused by a better feed conversion into milk and a higher utilization of the pasture. It has been found that feed production accounts for the main share of water input in livestock production (Singh et al., 2003). Feed management and animal management are seen as important measures for increasing the water productivity in livestock farming (Descheemaeker et al., 2010; Drastig et al., 2010).

The aim of this study is to quantify the influence of feed and livestock management strategies on the water productivity of milk in dairy farming for European conditions with milk yields up to 12,000 kg cow^{-1} year^{-1}. Various diets are combined with different milk yields and replacement rates to investigate their influence on water productivity of milk.

2. Materials and methods

2.1. System boundaries and data

This study analyzed the water productivity for milk production from cradle to farm-gate. The system comprises a defined number of dairy cows and their replacement. The replacement are calves and heifers, which are reared to recreate the dairy herd and to improve the genetics of the herd (Thornton, 2010). The system includes cow specific parameters, such as age at first calving, but also herd specific parameters, such as replacement rate. The replacement rate reflects the ratio of animals coming into the dairy herd to the average herd size (Kraatz, 2012). Pre-chains for the production of fertilizer, machines and buildings were excluded as well as transport and processing of milk and the water for cleaning, since they were found to be negligible (De Boer et al., 2012; Döring et al., 2013). Hence only water for feed production and drinking was considered in this study (Fig. 1.). The whole amount of water input was allocated to the milk as main product. In a case study for a commercial dairy farm in North-East Germany it was found that the contribution of slaughter cows to the revenues from the whole livestock system was about 10% only (Prochnow et al., 2012).

A typical dairy system located in Brandenburg, a part of North-East Germany, is modeled for the years 2008–2010. The herd size is assumed with 180 dairy cows of the race Holstein-Friesian and the milk yield is 8000 kg fat corrected milk (FCM) cow^{-1} year^{-1} (Kraatz, 2012). A kg(FCM) contains 4% fat and 3.4% protein. The replacement rate is defined with 40% according to the average replacement rate for the German state of Brandenburg (LKV BB, 2011). The female calves and heifers are reared at farm in a period of 25 months to become a cow (Spiekers and Potthast, 2004). The male calves are leaving the farm 14 days after their birth. The lactation period is 305 days with an additional 60 day dry period. The feed is presented as total mixed ratio (TMR) and a free-stall barn is considered as keeping system. The feed production is considered at typical sites of Brandenburg.

2.2. Calculation of water productivity

2.2.1. Definition of water productivity

This study provides several expressions of the water productivity of milk, such as kg fat corrected milk, food energy, food protein and Euro per m^3 of water input (W_{input}). W_{input} [m^3] is calculated according to Prochnow et al. (2012) as the sum of crop transpiration from precipitation $W_{\text{prec-transp}}$ [m^3], the irrigation water W_{irri} [m^3], and the drinking water of the animals W_{drink} [m^3].

$$W_{\text{input}} = W_{\text{prec-transp}} + W_{\text{irri}} + W_{\text{drink}} \tag{1}$$

This approach includes in the water input that fraction of precipitation that contributes to plant biomass generation, that is, transpiration. Soil evaporation is excluded from the water input as it is not involved in biomass generation and should be minimized. In contrast, the total amount of irrigation water is considered as water input since withdrawal, distribution and application are controlled and paid for by the farmers. Furthermore, irrigation water is distracted from its natural flow, which might cause environmental impacts.

The water productivity of the milk WP_{milk} [kg(FCM) m^{-3}] is defined by the *milk yield* in kg(FCM) per cow in a year related to the water input W_{input} [m^3].

$$WP_{\text{milk}} = \text{milk yield}/W_{\text{input}} \tag{2}$$

The water productivity of the food energy of milk $WP_{\text{milk-energy}}$ [MJ m^{-3}] is defined by the *food energy* of milk produced per cow in a year [MJ] related to the water input W_{input} [m^3]. The food energy of milk is 2.85 MJ kg(FCM)$^{-1}$ (USDA, 2013).

$$WP_{\text{milk-energy}} = \text{food energy}/W_{\text{input}} \tag{3}$$

The water productivity of the food protein of milk $WP_{\text{milk-protein}}$ [kg crude protein (CP$_{\text{food}}$) m^{-3}] is defined by the *food protein* of milk produced per cow in a year [kg(CP$_{\text{food}}$)] related to the water input W_{input} [m^3]. The food protein content of milk is 34 g(CP$_{\text{food}}$) kg(FCM)$^{-1}$.

$$WP_{\text{milk-energy}} = \text{food protein}/W_{\text{input}} \tag{4}$$

The water productivity of the milk on monetary base $WP_{\text{milk-revenues}}$ [€ m^{-3}] is defined by the *revenues* of milk produced per cow in a year [€] related to the water input W_{input} [m^3]. The average milk price of the years 2008, 2009 and 2010 is 0.3087 € kg(FCM)$^{-1}$ (MIL, 2012).

$$WP_{\text{milk-revenues}} = \text{revenues}/W_{\text{input}} \tag{5}$$

The water productivity of feed production WP_{feed} [kg dry matter (DM) m^{-3}] is defined as the water input W_{input} [m^3] for on-farm feed production and purchased feed production, e.g. soy bean meal. The output of feed is defined by the production of *dry matter* [kg(DM)] of single crops and feedstuffs related to their water input W_{input} [m^3].

$$WP_{\text{feed}} = \text{dry matter}/W_{\text{input}} \tag{6}$$

The water productivity of feed energy $WP_{\text{feed-energy}}$ [MJ net energy for lactation (NEL) m^{-3}] is defined as the feed energy

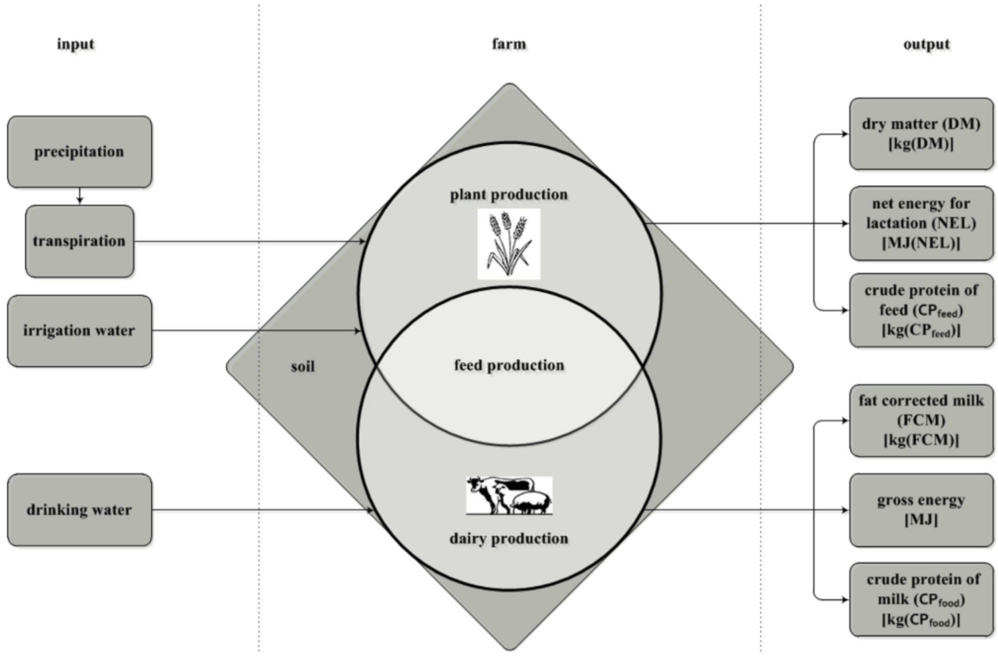

Fig. 1. System boundaries (Drastig et al., 2013 adapted).

Table 1
Classification of the arable land in soil groups (according to LELF (2010) and Kraatz (2012)).

Soil group	Agricultural growing region	Percentage of the arable land	Predominant soil texture
1	1	7.3	Clay, loam, loamy sand
2	2	22.2	Loamy sand
3	3	36.4	Loamy sand, sandy loam
4	4	27.1	Sand, loamy sand

production of *net energy for lactation* [MJ(NEL)] of single crops and feedstuffs (Table 3) related to their water input W_{input} [m^3].

$$WP_{feed\text{-}energy} = \text{net energy for lactation}/W_{input} \tag{7}$$

The water productivity of feed protein $WP_{feed\text{-}protein}$ [kg(CP$_{feed}$) m^{-3}] is defined as the feed protein production of *crude protein* [kg(CP$_{feed}$)] of single crops and feedstuffs (Table 3) related to their water input W_{input} [m^3].

$$WP_{feed\text{-}protein} = \text{crude protein}/W_{input} \tag{8}$$

2.2.2. Calculation of crop transpiration from precipitation

The water input for actual crop transpiration is calculated according to Prochnow et al. (2012) for the years 2008, 2009 and 2010 on a daily basis. This approach is based on the FAO 56 dual crop coefficient approach under non-standard conditions (Allen et al., 1998) and extended with a module in the ATB Modeling Database (Drastig et al., 2013) to consider crop water stress (Allen et al., 1998) and interception loss.

The rainfall interception loss calculation is based on work of von Hoyningen-Huene (1983) and Braden (1985). The approach was implemented in several agro-hydrological models for the estimation in particular of the interception for agricultural crops, e.g. the physical-based model SWAP (Kroes and van Dam, 2003) or in bucket models (Baroni, 2009). The general equation for canopy interception proposed is:

$$I = a + \text{LAI}\left(1 - \frac{1}{1 + \frac{cfP}{a\,\text{LAI}}}\right) \tag{9}$$

where *I* is the intercepted precipitation [mm], *P* is the gross precipitation [mm d^{-1}], *a* is an empirical coefficient [mm d^{-1}] and *cf* is the soil cover fraction ($1 - e^{-0.385}$ LAI [–]). For increasing precipitation amounts, the amount of intercepted precipitation asymptotically reaches the saturation amount *a LAI*. A value of $a = 0.25$ [mm d^{-1}] for the agricultural crops was assumed.

The FAO Penman–Monteith equation (Allen et al., 1998) is used to calculate the reference evapotranspiration ET_o [mm d^{-1}]. The potential evapotranspiration of a crop ET_c [mm d^{-1}] is determined by multiplying ET_o [mm d^{-1}] by the standard single crop coefficient K_c [–] (Allen et al., 1998).

$$ET_c = K_c ET_o \tag{10}$$

The crop coefficient K_c [–] can be split into a coefficient for crop transpiration (basal crop coefficient K_{cb} [–]) and soil evaporation coefficient K_e [–]. The potential crop transpiration T_c [mm d^{-1}], when the crop is not water stressed, is calculated by multiplying ET_o [mm d^{-1}] by the basal crop coefficient K_{cb} [–].

$$T_c = K_{cb} ET_o \tag{11}$$

K_{cb} changes over the growing season of the crop. The four growth stages are initial stage, crop development, mid-season, and late season. The values of K_{cb} of the initial stage $K_{cb,ini}$, the mid-season $K_{cb,mid}$ and at the end of the late season $K_{cb,end}$ of the feed crops (maize, oats, pasture, rye grass, sugar beet, winter barley, winter rape seed, winter rye, winter triticale, and winter wheat) are adopted from Allen et al. (1998). The initial stage $K_{cb,ini}$ is considered to be constant on a low level. During crop development the K_{cb} increases linearly to the value of $K_{cb,mid}$. At mid-season K_{cb} is constant. During late season the K_{cb} decreases linearly to $K_{cb,end}$.

The actual crop transpiration from precipitation $T_{act\text{-}prec}$ [mm d^{-1}] is calculated by multiplying the potential crop transpiration T_c [mm d^{-1}] by the transpiration reduction factor K_s [–].

$$T_{act\text{-}prec} = K_s K_{cb} ET_o \quad (12)$$

The transpiration reduction factor K_s [–] is necessary to consider water stress. The total available soil water in the root zone TAW [mm], the readily available soil water in the root zone RAW [mm] and the root zone depletion D_r [mm] are needed to calculate K_s [–].

$$K_s = \frac{TAW - D_r}{TAW\text{-}RAW} \quad (13)$$

The TAW [mm] is the amount of water actually available to the plants AWC [mm m^{-1}] in the rooting zone Z_r [m]. Z_r [m] increases linearly from the initial stage $Z_{r,ini}$ [m] to the maximum value at mid-season $Z_{r,max}$ [m] (Allen et al., 1998). The root lengths do not change anymore between mid-season and harvest. The data of *AWC* [mm] of different soil types in Brandenburg are available in the BÜK 300 (Soil overview map, Scale 1:300,000, State Office for Mining, Geology and Resources Brandenburg).

$$TAW = AWC\, Z_r \quad (14)$$

The readily available soil water in the root zone RAW [mm] is the fraction p_{adj} [–] of TAW [mm] which can be used by plants without water stress.

$$RAW = p_{adj} TAW \quad (15)$$

The depletion factor p [–] depends on the evapotranspiration. An adjustment is necessary to include the evapotranspiration rate ET_c [mm d^{-1}] (Allen et al., 1998).

$$P_{adj} = p + 0.04(5 - ET_c) \quad (16)$$

The actual crop transpiration originated from precipitation $W_{prec\text{-}transp}$ [m^3] is considered as sum of $T_{act\text{-}prec}$ [mm d^{-1}] over day d within the balance period.

$$W_{prec\text{-}transp} = \sum_{d=1}^{m} T_{act\text{-}prec}(d) \quad (17)$$

According to Prochnow et al. (2012) the balance period is the period between harvest of the previous crop $d = 1$ and harvest of the main crop m, which includes the period of fallow and the different crop growth stages. Winter rye, with an average harvest on 1st August, is chosen as previous crop of all main crops since winter rye has a proportion of 40% of all cereals in Brandenburg (MIL, 2012). The weather data of all weather stations located in Brandenburg are used for the calculation of the actual crop transpiration. The meteorological stations are run by Germany's National Meteorological Service (Deutscher Wetterdienst—DWD). The average temperature in Brandenburg for the years 1971 to 2000 was 9.0 °C and the average rainfall was 553 mm (DWD, 2013). The average temperature in Brandenburg for the years 2008, 2009 and 2010 was 9.2 °C and the average rainfall was 659 mm (DWD, 2013). Lahmer et al. (2001) expect that climate changes will increase the pressure on water resources in North-East Germany. Weather data and the specific plant production processes for soybeans are considered for Argentinian and Brazilian conditions (Prochnow et al., 2012), because 70% of the soybeans are imported from these countries (Statistisches Bundesamt, 2010).

2.2.3. Calculation of drinking water demand

2.2.3.1. Dairy cows. The daily drinking water demand of the dairy cows is calculated according to Meyer et al. (2004) and Jeroch et al. (1999). Meyer et al. (2004) calculated the daily water intake $W_{drink\text{-}cow\_daily}$ [L d^{-1}] based on the average ambient temperature T [°C], the milk yield per day Y_{milk} [kg(FCM) d^{-1}], the body weight m_b [kg] and the sodium intake In_{Na} [g d^{-1}] for the day of the year o:

$$W_{drink\text{-}cow\_daily}(o) = -26.12 + 1.5Y_{milk}(o) + 0.085m_b + 0.406In_{Na}(o) \quad (18)$$

The sodium demand per cow and day In_{Na} [g d^{-1}] is 0.011 g kg^{-1} m_b for maintenance and 0.5 g kg(FCM)$^{-1}$ Y_{milk} for milk yield with an usability of 85% (Jeroch et al., 1999).

$$In_{Na}(o) = 0.013m_b + 0.6Y_{milk} \quad (19)$$

Eqs. (18) and (19) can be merged to Eq. (20) to reduce the number of variables.

$$W_{drink\text{-}cow\_daily}(o) = -26.12 + 1.516T(o) + 1.538Y_{milk}(o) + 0.063m_b \quad (20)$$

The annual drinking water intake $W_{drink\text{-}cow}$ [m^3 a^{-1}] is calculated by cumulating the daily drinking water demand $W_{drink\text{-}cow\_daily}$ [L d^{-1}] over the day of the year o.

$$W_{drink\text{-}cow} = \sum_{o=1}^{365} W_{drink\text{-}cow\_daily}(o) \quad (21)$$

2.2.3.2. Replacement. The drinking water demand of the replacement $W_{drink\text{-}replacement\_daily}$ [L d^{-1}] is calculated according to KTBL (2008) depending on the live-weight of the calves and heifers m_r [kg] at day of live n.

$$W_{drink\text{-}replacement\_daily}(n) = 6.46 + 0.0728m_r \quad (22)$$

The drinking water intake of the replacement $W_{drink\text{-}replacement}$ [m^3] is calculated by cumulating of the daily drinking water demand $W_{drink\text{-}replacement\_daily}$ [L d^{-1}] over the days of the rearing period n.

$$W_{drink\text{-}replacement} = \sum_{n=1}^{760} W_{drink\text{-}replacement\_daily}(n) \quad (23)$$

2.3. Feed production

Four agricultural growing regions of Brandenburg are used to summarize the specific soil characteristics and soil types of the arable land in Brandenburg according to the State Office for Rural Development, Agriculture and Reorganization of Land (LELF, 2010) (Table 1). For pasture four yield groups are considered in this study (Table 2). Brandenburg was divided into 20,000 polygons to combine the agricultural growing regions for arable land, the yield groups for pasture and the soil overview map. Four soil groups were introduced to summarize similar characteristics. Farm specific data would be used in case of adopting the method to an individual farm.

Four soil groups are characterized by specific growing conditions, such as yields, seed and harvest dates and fertilization (Kraatz, 2012). The water productivity of the different crops is calculated for each soil group with its soil characteristics (Tables 1 and 2) and specific growing conditions. Yields, seeding and harvest dates, energy content and crude protein content of all feed crops and grass are shown in Table 3. Seed and harvest dates of the crops are considered to be equal in all soil groups to eliminate the effect of the seed and harvest date on the water productivity. The water productivity of pasture is calculated for every grazing period and of rye grass for every cut. The mean WP_{feed} is calculated with the weighted average over all soil groups within one crop. Not all crops are appropriate for each soil group, e.g. sugar beets are

Table 2
Classification of the permanent grassland in soil groups (according to LELF (2010) and Kraatz (2012)).

Soil group	Yield in t DM[a] ha^{-1} $year^{-1}$	Number of cuts	Soil characteristics
1	9	5	Homogeneous fen, half-bog, humus sands, well regulated soil water conditions
2	7	4	Heterogeneous fen, humus sands, changing soil water conditions
3	5	3	Heterogeneous degraded fen, changing soil water conditions
4	5	3	Heterogeneous fen, humus sands, changing soil water conditions, extensive cultivation without use of fertilizer

[a] DM = dry matter.

Table 3
Yield (LELF, 2010), seed date and harvest date, energy and crude protein content (Spiekers and Potthast, 2004) of the crops for the soil groups. Harvest of the pre-crop winter rye for each crop is 1st August.

Crop	Dry matter yield in t ha^{-1} a^{-1} in soil group				Seed date	Harvest date	Feed quality traits	
	1	2	3	4			MJ(NEL[a]) kg(DM[b])$^{-1}$	kg(CP[c]) kg(DM)$^{-1}$
Hay	10.0	8.8	6.8	5.0	–	–	5.3	0.12
Pasture	9.0	7.0	5.0	5.0	–	–	6.4	0.18
Rye grass (all cuts)	11.0	9.5	7.5	5.0	–	–	6.0	0.17
Rye grass 1st cut	2.8	3.3	3.4	2.3	–	–	6.6	0.15
Maize for silage	12.0	11.0	9.5	7.5	20. April	20. September	6.4	0.09
Sugar beet	12.7	11.5	10.4	–	15. March	15. October	7.3	0.11
Maize for grain	6.9	6.0	5.2	–	20. April	20. October	8.4	0.11
Oats	4.3	3.3	2.6	1.9	20. February	20. July	7.0	0.12
Winter barley	6.0	5.2	4.1	3.1	15. September	14. July	8.1	0.12
Winter rape seed	3.8	3.3	2.7	2.0	25. August	27. July	7.2	0.39
Winter rye	6.4	5.8	4.7	3.6	01. October	01. August	8.5	0.11
Winter triticale	5.7	5.2	4.0	3.1	01. October	31. July	8.3	0.15
Winter wheat	6.5	5.4	4.3	3.3	05. October	05. August	8.5	0.15

[a] NEL = net energy for lactation.
[b] DM = dry matter.
[c] CP = crude protein.

grown only in the soil groups 1–3 due to the requirements of the plants on soil quality. The water input of crops with more than one product, such as soy beans, rape seed and beet pulps, is allocated on mass basis to the single products.

2.4. Diets

2.4.1. Diets of the dairy cows

The diets used in this study are appropriate for the ruminant nutrition to cover the demand of maintenance and milk yield in terms of net energy, crude protein and crude fiber (GfE, 2001). They were developed for different milk yields, stages of lactation, and seasons and cover most of the production conditions from extensive (low input) to intensive (high input) dairy systems in North-East Germany. The ingredients of the dairy diets are grass silage, maize silage, hay, pasture, beet pulp silage, soy bean meal, rapeseed meal, triticale (*Triticosecale* Wittm.) and concentrate. The concentrate consists of 47% winter rye, 25% rape seed meal, 12% winter wheat, 10% oats, 3% winter barley, 2% molasses and 1% maize grain. The dairy diet is presented as total mixed ration (TMR).

Based on a balanced standard diet, with 27% grass silage, 23% maize silage, 20% pasture, 26% concentrate, 1% hay, and 3% beet pulp silage, further diets are derived by maximizing the components grass silage, maize silage, pasture and concentrate. The diets were adapted to the considered milk yield of 4000, 6000, 8000, 10,000, and 12,000 kg(FCM) cow^{-1} $year^{-1}$. Specific live weights were assigned to the several milk yields with attention to the physiological conditions of the cows, e.g. the maximum feed intake (Spiekers and Potthast, 2004). Beginning with a live weight of 500 kg at a milk yield of 4000 kg(FCM) cow^{-1} $year^{-1}$ the live weight increases by 50 kg per 2000 kg increase in milk yield. An increase of 100 kg live weight increases the dry matter intake by 0.6–1.2 kg d^{-1} (Kirchgeßner, 2004).

Within one year cows have varying nutritional demand depending on stage of lactation and gestation. The lactation period of 305 days is divided in a high performance period of 103 days and a 202 days period of decreasing milk yield. The dry period is divided in a beginning period of 45 days and an ending period of 15 days. At the end of the dry period the nutrient demand of the cows are higher than in the beginning, because of the increasing demand of the unborn calf. Four diets are needed to meet the demand of the four periods and each of them were divided in summer and winter diets, since pasture is available only in summer (Table 4).

The feed intake per cow in a year is shown in Table 5 exemplarily for a milk yield of 8000 kg(FCM) cow^{-1} $year^{-1}$. Table 6 shows the dry matter intake of the cows per year at various milk yields and diets.

2.4.2. Diets of the replacement

The replacement process, including calves and heifers, is calculated according to the methodology described by Kraatz (2012) as best practice in North-East Germany. The diets for the replacement are calculated to cover the nutrition demand of maintenance and daily gain. Two systems of the replacement process are described: a system with grazing during summer and a whole-year confinement system. The feed intake for calves and heifers is presented in Table 7. To determine the influence of the replacement rate on the water productivity of milk, the replacement rate is varied between 10% and 50%.

3. Results and discussion

3.1. Water input and water productivity of the feed

The water input of the individual feed crops which is equal to the transpiration from precipitation $W_{prec\text{-}transp}$ varies strongly (Fig. 2). The first cut of rye grass has the lowest transpiration with an average of 200 mm and rye grass over the whole season transpires

Table 4
Diets for the different stages of lactation and gestation during the year at a milk yield of 8000 kg $year^{-1}$ and a balanced feeding with half-day grazing in summer.

Stage of lactation and gestation	Season	Feed intake [kg(DM[a]) cow^{-1} $period^{-1}$]	Feed composition in %					
			Grass silage	Maize silage	Pasture	Hay	Beet pulps	Concentrate
First 103 DIM[b]	Summer	1076	14	24	31	–	–	31
	Winter	1061	27	27	–	–	10	36
104–305. DIM	Summer	1742	20	20	35	–	–	25
	Winter	1752	40	29	–	–	6	25
60–16. day a.p.[c]	Summer	198	–	–	100	–	–	–
	Winter	207	78	–	–	22	–	–
15 days a.p.	Summer	92	–	–	87	–	–	13
	Winter	82	60	28	–	–	–	12

[a] DM = dry matter.
[b] DIM = days in milk.
[c] a.p. = ante partum, time before calving.

Table 5
Annual feed intake of the dairy cow (milk yield 8000 kg $year^{-1}$).

Diet	Grazing in summer	Maximized ingredient	Feed intake [kg(DM[a]) cow^{-1} $year^{-1}$]	Feed composition in %					
				Grass silage	Maize silage	Pasture	Hay	Beet pulps	Concentrate
1	–	Balanced	6195	39	26	–	1	7	27
2	–	Concentrate	6065	34	24	–	1	2	39
3	–	Grass silage	6559	70	23	–	1	–	6
4	–	Maize silage	6137	7	65	–	1	–	27
5	Half-day	Balanced	6211	27	23	20	1	3	26
6	Half-day	Concentrate	6071	17	21	20	3	1	38
7	Half-day	Grass silage	6400	50	18	19	1	–	12
8	Half-day	Maize silage	6163	3	49	20	1	–	27
9	Full-day	Balanced	6165	20	13	40	1	3	23
10	Full-day	Concentrate	6084	17	12	39	1	1	30
11	Full-day	Grass silage	6341	36	12	38	1	–	13
12	Full-day	Maize silage	6092	3	33	39	1	–	24

[a] DM = dry matter.

585 mm. Winter rye has the lowest transpiration of all grains with 260 mm and winter triticale the highest with 460 mm. Transpiration of the same crop is similar for the four soil groups, except for sugar beets and maize for grain. The transpiration of sugar beets and maize is highest in soil group 1 and decreases with lower quality of the soil and amount of available water.

The mean WP_{feed} and the standard deviation of each crop within the soil groups are shown in Fig. 3. The WP_{feed} varies strongly within crops on different sites and among crops from 0.6 kg(DM) m^{-3} for rape seed to 3.4 kg(DM) m^{-3} for maize silage. Sugar beets and maize silage have the highest WP_{feed} on dry matter basis with an average of 3.1 kg(DM) m^{-3} and 2.6 kg(DM) m^{-3}, respectively. Grain

Table 6
Feed dry matter intake per year at various milk yields and diets.

Maximized ingredient	Milk yield in kg fat corrected milk per cow and year				
	4000	6000	8000	10,000	12,000
	Feed intake [kg dry matter cow^{-1} $year^{-1}$]				
Balanced	4260	5140	6190	7250	8070
Concentrate	3950	5180	6070	7070	7990
Grass silage	4340	5350	6430	7230	8090
Maize silage	4210	5250	6130	7180	8040

Table 7
Feed intake of the calves and heifers adapted to Kraatz (2012).

Keeping system	Feed intake [kg(DM[a]) $animal^{-1}$ $year^{-1}$]	Feed composition				
		Grass silage	Maize silage	Pasture	Hay	Concentrate
Grazing during summer	4185	24%	20%	43%	1%	12%
Whole-year confinement	4430	46%	37%	–	1%	16%

[a] DM = dry matter.

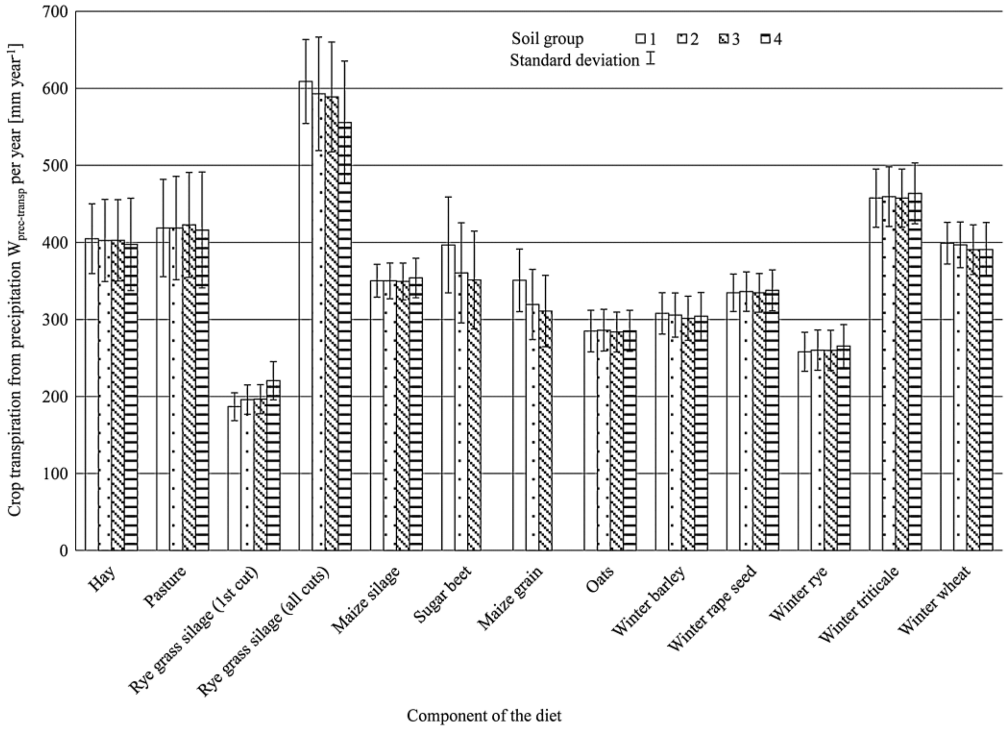

Fig. 2. Total seasonal transpiration [mm] of the components of the diet at different soil groups.

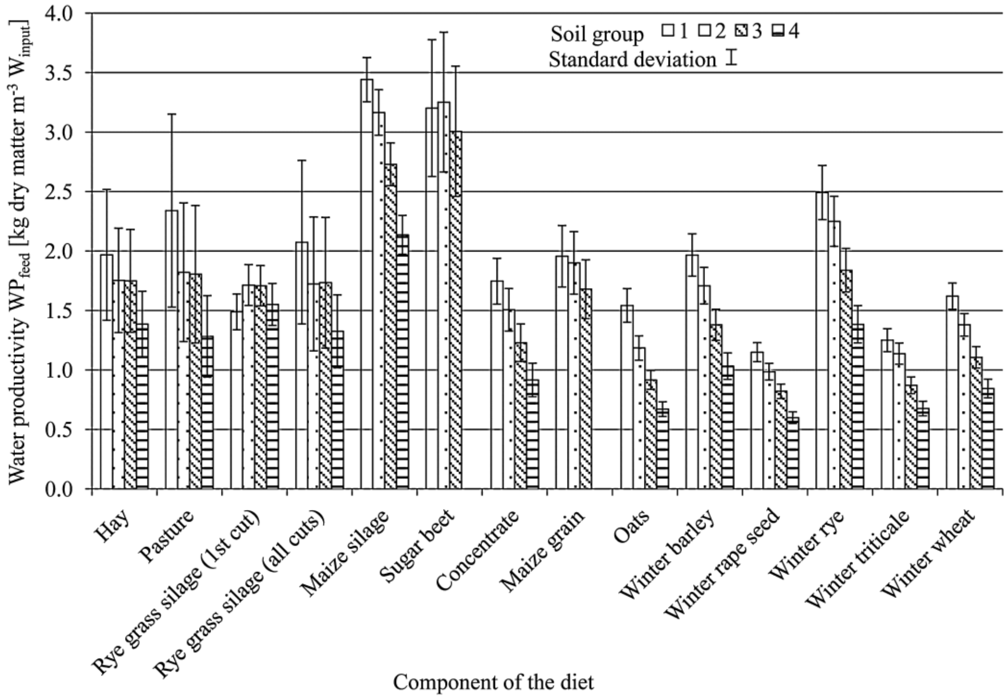

Fig. 3. Water productivity of the components of the diet at different soil groups.

Table 8
Water productivity of the feedstuffs on the basis of dry mass, crude protein and energy content (values in brackets are the standard deviation).

Component of the diet	Water productivity of feed production [kg(DM[a]) m^{-3}]	Water productivity of feed protein [kg(CP$_{feed}$[b]) m^{-3}]	Water productivity of feed energy [MJ NEL[c] m^{-3}]
Hay	1.6 (±0.6)	0.19 (±0.07)	8.5 (±3.0)
Pasture	1.6 (±0.6)	0.29 (±0.11)	10.4 (±3.8)
Rye grass silage (all cuts)	1.6 (±0.5)	0.26 (±0.09)	9.6 (±3.2)
Rye grass silage (1st cut)	1.6 (±0.2)	0.24 (±0.03)	10.8 (±1.3)
Maize silage	2.6 (±0.5)	0.22 (±0.04)	16.5 (±2.9)
Sugar beet	3.1 (±0.6)	0.34 (±0.06)	22.6 (±3.8)
Concentrate	1.2 (±0.4)	0.20 (±0.08)	7.6 (±2.6)
Maize grain	1.8 (±0.3)	0.19 (±0.03)	14.8 (±2.3)
Oats	0.9 (±0.2)	0.11 (±0.03)	6.2 (±1.7)
Soy beans	0.4	0.22	3.7
Winter barley	1.3 (±0.3)	0.16 (±0.04)	10.6 (±2.5)
Winter rape seed	0.8 (±0.2)	0.30 (±0.07)	5.5 (±1.3)
Winter rye	1.6 (±0.5)	0.18 (±0.06)	13.4 (±4.4)
Winter triticale	0.8 (±0.2)	0.12 (±0.03)	7.0 (±1.6)
Winter wheat	1.1 (±0.2)	0.15 (±0.04)	9.0 (±2.1)

[a] DM = dry matter.
[b] CP$_{feed}$ = crude protein of feed.
[c] NEL = net energy for lactation.

and concentrate have the lowest WP$_{feed}$ of all investigated feed stuffs, except maize for grain. Winter rye has nearly twice the WP$_{feed}$ of winter wheat. The grass-based components of the diet have a WP$_{feed}$ between maize silage and grain with an average of 1.6 kg(DM) m^{-3}. It is detectable that from soil group 1 to soil group 4 the WP$_{feed}$ decreases within all crops, except sugar beets and rye grass silage from first cut. This is explained by the lower soil quality and the reduced yield and not by an increased transpiration (see Table 3 and Fig. 2). The differences between the crops are caused by differences in yield and in transpiration.

A large variation in water productivity of different crops in various sites and soil qualities is also described by Molden et al. (2010). With respect to single feed crops, the water productivity of maize for grain in Lebanon is reported to be 10% higher than in this study and of maize silage 10% lower (Karam et al., 2003), of maize for grain in India slightly lower (Sampathkumar et al., 2012) and of maize for grain in Portugal 20% lower and for wheat 30% higher (Rodrigues and Pereira, 2009). In contrast to this study, the authors included soil evaporation in the water use and irrigation has an important share of the total water use. Hence, the variation in water productivity between the studies may at least partly be due to differing methodologies.

The linear relation between yield and transpiration as described by Passioura (2006) is not observed in this study. However, the difference between the potential and the actual transpiration is low caused by sufficient precipitation, which is 20% higher in the three investigated years 2008–2010 than in the 30-year reference period 1971–2000 (DWD, 2013). So the available water is not the limiting factor of plant growth within the soil groups, except sugar beets and maize for grain, in the study period. The variation of WP$_{feed}$ of sugar beets and maize for grain is low between the soil groups due to a simultaneous decrease in yield and transpiration (Fig. 3). The WP$_{feed}$ of the grain is low since the yield is lower than that for roughage. Winter rye and winter wheat have a similar yield and so the variation in WP$_{feed}$ is caused by the lower transpiration of winter rye. The high WP$_{feed}$ of sugar beet and maize silage is caused by the high yields of these crops and not by low transpiration.

The average water productivity on mass basis WP$_{feed}$, protein basis WP$_{feed\text{-}protein}$ and energy basis WP$_{feed\text{-}energy}$ is shown in Table 8. Sugar beets have the highest WP$_{feed\text{-}protein}$ with 0.34 kg(CP$_{feed}$) m^{-3} and the highest WP$_{feed\text{-}energy}$ with 22.6 MJ(NEL) m^{-3}. Maize silage has the second highest WP$_{feed\text{-}energy}$ with 16.5 MJ(NEL) m^{-3} but only an average WP$_{feed\text{-}protein}$ with 0.22 kg(CP$_{feed}$) m^{-3}. Rape seed has the second highest WP$_{feed\text{-}protein}$ with 0.3 kg(CP$_{feed}$) m^{-3} but the lowest WP$_{feed\text{-}energy}$ of the crops grown in Brandenburg with 5.5 MJ(NEL) m^{-3}. Oats has the lowest WP$_{feed\text{-}protein}$ with 0.11 kg(CP$_{feed}$) m^{-3} and the third lowest WP$_{feed\text{-}energy}$ with 6.2 MJ(NEL) m^{-3}. The other feed stuffs have WP$_{feed\text{-}protein}$ and WP$_{feed\text{-}energy}$ between oats and rape seed and sugar beets.

The high water productivity on mass basis of maize silage does not lead to a high water productivity on protein basis. Maize silage

Table 9
Total water use per cow per year at various milk yields and feeding strategies including water for feed production, drinking and replacement.

Diet	Grazing in summer	Maximized ingredient	Milk yield in kg fat corrected milk per cow and year				
			4000	6000	8000	10,000	12,000
			Total water use [m^{-3} cow^{-1} year^{-1}]				
1	–	Balanced	3529	4202	5262	5980	7191
2	–	Concentrate	4166	4410	5564	6501	7679
3	–	Grass silage	3727	4292	5009	5729	7346
4	–	Maize silage	3372	4228	5006	5792	7432
5	Half-day	Balanced	3786	4272	5264	6127	7223
6	Half-day	Concentrate	4135	4388	5561	6579	7598
7	Half-day	Grass silage	3626	4251	5162	6114	7349
8	Half-day	Maize silage	3266	4014	5014	5791	7298
9	Full-day	Balanced	3529	4334	5371	6194	–
10	Full-day	Concentrate	3863	4438	5536	6457	–
11	Full-day	Grass silage	3628	4379	5249	6065	–
12	Full-day	Maize silage	3450	4346	5253	6100	–

Table 10
Water productivity of milk on mass basis, food energy basis, food protein basis and monetary basis at various milk yields and feeding strategies.

Diet	Grazing in summer	Maximized ingredient	Milk yield in kg fat corrected milk per cow and year				
			4000	6000	8000	10,000	12,000
Water productivity of milk [kg fat corrected milk m^{-3}]							
1	–	Balanced	1.1	1.4	1.5	1.7	1.7
2	–	Concentrate	1.0	1.4	1.4	1.5	1.6
3	–	Grass silage	1.1	1.4	1.6	1.7	1.6
4	–	Maize silage	1.2	1.4	1.6	1.7	1.6
5	Half-day	Balanced	1.1	1.4	1.5	1.6	1.7
6	Half-day	Concentrate	1.0	1.4	1.4	1.5	1.6
7	Half-day	Grass silage	1.1	1.4	1.5	1.6	1.6
8	Half-day	Maize silage	1.2	1.5	1.6	1.7	1.6
9	Full-day	Balanced	1.1	1.4	1.5	1.6	–
10	Full-day	Concentrate	1.0	1.3	1.4	1.5	–
11	Full-day	Grass silage	1.1	1.4	1.5	1.6	–
12	Full-day	Maize silage	1.2	1.4	1.5	1.6	–
Water productivity of food energy [MJ m^{-3}]							
1	–	Balanced	3.2	4.1	4.3	4.8	4.8
2	–	Concentrate	2.7	3.9	4.1	4.4	4.5
3	–	Grass silage	3.1	4.0	4.5	5.0	4.7
4	–	Maize silage	3.4	4.0	4.5	4.9	4.6
5	Half-day	Balanced	3.0	4.0	4.3	4.6	4.7
6	Half-day	Concentrate	2.8	3.9	4.1	4.3	4.5
7	Half-day	Grass silage	3.1	4.0	4.4	4.7	4.6
8	Half-day	Maize silage	3.5	4.2	4.5	4.9	4.7
9	Full-day	Balanced	3.2	3.9	4.2	4.6	–
10	Full-day	Concentrate	3.0	3.8	4.1	4.4	–
11	Full-day	Grass silage	3.1	3.9	4.3	4.7	–
12	Full-day	Maize silage	3.3	3.9	4.3	4.7	–
Water productivity of food protein [kg(CP_{food}[a]) m^{-3}]							
1	–	Balanced	0.04	0.05	0.05	0.06	0.06
2	–	Concentrate	0.03	0.05	0.05	0.05	0.05
3	–	Grass silage	0.04	0.05	0.05	0.06	0.06
4	–	Maize silage	0.04	0.05	0.05	0.06	0.05
5	Half-day	Balanced	0.04	0.05	0.05	0.06	0.06
6	Half-day	Concentrate	0.03	0.05	0.05	0.05	0.05
7	Half-day	Grass silage	0.04	0.05	0.05	0.06	0.06
8	Half-day	Maize silage	0.04	0.05	0.05	0.06	0.06
9	Full-day	Balanced	0.04	0.05	0.05	0.05	–
10	Full-day	Concentrate	0.04	0.05	0.05	0.05	–
11	Full-day	Grass silage	0.04	0.05	0.05	0.06	–
12	Full-day	Maize silage	0.04	0.05	0.05	0.06	–
Water productivity of milk on monetary base [€ m^{-3}]							
1	–	Balanced	0.35	0.44	0.47	0.52	0.52
2	–	Concentrate	0.30	0.42	0.44	0.47	0.48
3	–	Grass silage	0.33	0.43	0.49	0.54	0.50
4	–	Maize silage	0.37	0.44	0.49	0.53	0.50
5	Half-day	Balanced	0.33	0.43	0.47	0.50	0.51
6	Half-day	Concentrate	0.30	0.42	0.44	0.47	0.49
7	Half-day	Grass silage	0.34	0.44	0.48	0.50	0.50
8	Half-day	Maize silage	0.38	0.46	0.49	0.53	0.51
9	Full-day	Balanced	0.35	0.43	0.46	0.50	–
10	Full-day	Concentrate	0.32	0.42	0.45	0.48	–
11	Full-day	Grass silage	0.34	0.42	0.47	0.51	–
12	Full-day	Maize silage	0.36	0.43	0.47	0.51	–

[a] CP_{food} = crude protein of food.

has the lowest protein content of the investigated feeds (Spiekers and Potthast, 2004). However, the high dry matter yield leads to high energy and protein yields per hectare. So the water productivity on energy basis is high but only average on protein basis. Rape seed meal shows the opposite effect. It has a low yield, a low WP_{feed} on mass basis, is poor in energy but rich in protein when compared with the other concentrates (Spiekers and Potthast, 2004). However, the water productivity on protein basis is the second highest after sugar beets. Sugar beets show on mass, protein and energy base the highest water productivity of all investigated feed stuffs since the high dry matter yield also lead to high energy and protein yields. However, a sugar beet based diet is not possible in terms of ruminant appropriate feeding since the maximum daily intake of sugar beets should not exceed 5 kg. The WP_{feed} on mass basis is not the only meaningful indicator for water productivity, since high or low WP_{feed} on mass basis for specific feed stuffs, like maize silage or rape seed, do not lead to high or low WP_{feed} on protein and energy basis in the same way.

3.2. Water input and water productivity of dairy production

The total water input per cow per year including the water input of feed production, the drinking water, and the water input of the replacement is shown in Table 9. At 4000 kg(FCM) the water input amounts on average 3700 m^3. To produce twice the amount of milk

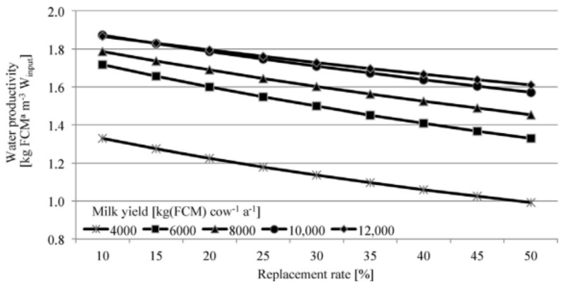

Fig. 4. Influence of the replacement rate on WP_{milk} at various milk yield with a balanced feeding with half-day grazing in summer. [a]FCM = fat corrected milk (4% fat, 3.4% protein)

the water input is 40% higher and to produce the threefold milk yield of 12,000 kg(FCM) twice the water input, 7400 m^3, is needed.

The water productivity of the dairy production is shown in Table 10. For a milk yield of 8000 kg(FCM) the investigation results in an average WP_{milk} of 1.5 kg(FCM) m^{-3}, $WP_{milk\text{-}energy}$ of 4.3 MJ m^{-3}, $WP_{milk\text{-}protein}$ of 0.05 kg crude protein m^{-3} and $WP_{milk\text{-}revenues}$ of 0.47 € m^{-3}. The WP_{milk}, $WP_{milk\text{-}energy}$, $WP_{milk\text{-}protein}$ and $WP_{milk\text{-}revenues}$ are the lowest in the system with 4000 kg(FCM) with an average decrease of 30% compared to the milk yield of 8000 kg(FCM). The WP_{milk} is 10% lower on average for 6000 kg(FCM). Milk yields of 10,000 and 12,000 kg(FCM) show on average a 7% higher WP_{milk} than for 8000 kg(FCM). The increase of the milk yield results in an increase of the WP_{milk}, but this effect diminishes at milk yields of 10,000 kg(FCM) and above. The highest $WP_{milk\text{-}energy}$ with 5.0 MJ m^{-3} is found at 10,000 kg(FCM) and a grass silage based feeding without grazing.

The low WP_{milk} at low milk yields is caused by the ruminant-appropriate feeding with the focus on covering the demand for crude fiber and not the energy and protein demand. To maintain the rumination process, diets have to include components that are rich in crude fiber and less water productive, especially grass. However, the cows with the lowest milk yield in this study have a higher milk yield than the Holstein-Friesian cows under African conditions (Haile et al., 2009). Holstein-Friesian cows are adapted to the climate conditions of western Europe and can tap their full genetic potential. A further increase of genetic potential by crossbreeding is not a suitable way to increase WP_{milk} as described for African and Indian conditions (Descheemaeker et al., 2010; Haile et al., 2009; Haileslassie et al., 2011). The feed conversion into milk increases at higher milk yields (Descheemaeker et al., 2010; Zonderland-Thomassen and Ledgard, 2012) since the demand for maintenance and the demand for yield is shifting to the demand for yield. The water demand for rearing the replacement is shared to the milk yield such as the demand for maintenance. At higher milk yields this effect is not that distinctive as at low milk yields and so the increase in WP_{milk} stagnates at 10,000 kg(FCM). Another reason of the stagnation of WP_{milk} at milk yields above 10,000 kg(FCM) is caused by the high-producing feeding management. For covering the nutrient demand of the high-producing dairy cows the nutrient content of the feed has to be higher, because the feed-intake-capacity of the cows is limited (Spiekers and Potthast, 2004). To fill this gap more concentrates and high quality forages have to be fed. These components have a lower WP_{feed} on mass basis than those with a lower nutrient content as shown in Table 8 and described by Blümmel et al. (2009). For that reason, the effect of decreasing the share of feed for maintenance at higher milk yields is negated.

An increase in WP_{milk} of maize silage based diets is not observed in contrast to Passioura (2006). The maize silage based diets have to be supplemented with rape seed meal or soy bean meal to balance the nutritional demand of the dairy diet. Feeding more crop by-products, such as soy bean meal, and rape seed meal, does not lead to an increased water productivity of milk as described in Descheemaeker et al. (2010) for African conditions where the water input is allocated to the main product oil only. In our study, the high WP_{feed} of maize silage with 2.6 kg(DM) m^{-3} is negated by the use of protein-rich concentrates. The low WP_{feed} of the concentrates decreases the WP_{milk} of the concentrate based diets. The grazing management shows a small effect on WP_{milk} since the WP_{feed} of pasture and the grass silage are equal at 1.6 kg(DM) m^{-3}. On protein and energy basis the water productivity of pasture and grass silage is similar, too.

At low milk yields the milk yield show a higher influence on WP_{milk} than the feeding strategy. At milk yields of 8000 kg(FCM) and above the feeding management has a higher influence on WP_{milk}.

3.3. *Influence of the replacement rate on the water productivity of milk*

The water input for rearing the replacement has an important proportion of total water input. The share of water input for the replacement decreases with an increasing milk yield. At a replacement rate of 40% and a milk yield of 4000 kg(FCM), 28% of the total water input is needed by the calves and heifers. At the same replacement rate and a milk yield of 12,000 kg(FCM), only 14% of the water input is caused by the replacement. Fig. 4 shows the influence of various replacement rates on the WP_{milk}. The effect is demonstrated on a diet with balanced composition and half-day grazing in summer. Rearing a heifer with whole year confinement needed 2570 m^3 and with grazing during summer 2540 m^3. Over all milk yields the WP_{milk} decreases by 2.7% with an increase in the replacement rate by 5%. At a replacement rate of 10% WP_{milk} was 0.3 kg(FCM) m^{-3} higher than at a replacement rate of 50%. An equal WP_{milk} of 1.6 kg(FCM) $m^{-3}$was reached at a milk yield of 6000 kg(FCM) and a replacement rate of 20%, at 8000 kg and 30%, at 10,000 kg and 45% and at 12,000 kg and 50%, respectively.

The replacement rate is a herd specific parameter and so the influence on water productivity can only be regarded with respect to a whole dairy herd. High milk yields of dairy cows and high replacement rates are comparable in terms of WP_{milk} with low yield and low replacement rate system. The decrease of WP_{milk} at higher replacement rates was expected, since the share of the water input for rearing the calves and heifers on the total W_{input} increases. At the economical recommended replacement rate of 25% (Weiher, 2004) WP_{milk} was 0.1 kg(FCM) m^{-3} higher than at the current replacement rate in Brandenburg of 40%. So the potential for improving the WP_{milk} with a reduction of the replacement rate is low.

4. Conclusions

Management strategies to improve the water productivity of milk production under conditions of North-East Germany, such as varying milk yield, feeding strategies, and replacement rates, can be used alone or in combination. Among these management strategies, the milk yield has the strongest influence on the water productivity of milk production. Particularly an increase in milk yield from a low to an intermediate level leads to a pronounced increase in water productivity, while an increase from a high milk yield to a very high milk yield does not further increase water productivity. Increasing the milk yield up to 10,000 kg(FCM) per cow and year would be favorable in terms of water productivity. Diets affect water productivity as well. They should contain mostly roughage, such as grass silage, maize silage, and pasture, and only few concentrates. The influence of the replacement rate on water productivity is low. The actual replacement rate should not be further increased. The method applied here with regional data can be adopted on farm scale as well to provide strategies for increasing the water productivity of milk in individual farms.

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ORIGINAL RESEARCH

Water productivity of poultry production: the influence of different broiler fattening systems

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Abstract

With the expected increase in poultry meat consumption water use will increase as well. The objective of this study is to quantify the effects of fattening systems on the water productivity in broiler chicken production with consideration given to conditions in Germany. Four fattening systems were analyzed in terms of water use for feed production, drinking, cleaning, and the parent stock. The fattening systems differed in intensity, ranging from fast fattening with a fattening period of 30 days and a carcass weight of 1.1 kg to slow fattening with a period up to 46 days and a carcass weight of 2.1 kg. During the fattening period the broiler chicken were fed with performance-linked feed. The water productivity of the feed components varied from 0.4 kg dry mass per m^3 water input for soybean meal to 1.8 kg dry mass per m^3 water input for maize. In all fattening systems the water input for feed production accounted for 90 to 93% of the total water input. The share for the parent stock was 7 to 10%, while drinking and cleaning water accounted for less than 1%. For all fattening systems the water productivity was 0.3 kg carcass weight per m^3 water input, 2.8 MJ food energy per m^3 water input and 57 g food protein per m^3 water input. The shorter fattening period and lower feed demand in the more intensive fattening systems were juxtaposed to the higher carcass weight and higher water productivity of the feed components in the more extensive systems.

Introduction

The world population is growing. It is estimated that in 2050 there will be 9.3 billion people living on the earth (UNDESA 2011). Besides the increasing number of people, diets are changing to include more meat. Meat production is expected to increase by 1.6% per year from 2013 to 2022. Fifty percent of this additional meat is predicted to be poultry such that poultry production will increase by 1.9% per year (OECD 2013). Poultry is a meat type acceptable to all major religious and cultural groups (Steinfeld et al. 2006). In 2022, poultry is projected to account for 37% of global meat supply and to be the world's largest meat sector (OECD 2013). Poultry production in Germany increased from 0.9 million tons in 2003 to 1.4 million tons in 2012 (Statistisches Bundesamt [German Federal Statistical Office] 2013). Sixty percent of German poultry production is generated by broiler chicken (Statistisches Bundesamt [German Federal Statistical Office] 2013). In 2003, 0.5 million tons of broiler meat were produced (Statistisches Bundesamt [German Federal Statistical Office] 2013). In 2012, 0.9 million tons of Germany's total poultry production were accounted for by broiler meat (Statistisches Bundesamt [German Federal

Statistical Office] 2013). This trend is expected to continue through the coming years (OECD 2013).

The increasing consumption of animal products leads to higher pressure on global resources such as land, energy, and water (Pimentel et al. 1997). Agriculture is competing with domestic and industrial uses for water (Postel 2000). In addition, climate changes are expected to increase the pressure on water resources (Gerstengarbe et al. 2003). To meet these challenges of global change, agricultural productivity must be increased.

Studies of the water use in livestock production systems focus mainly on water demand for milk and beef production (Armstrong et al. 2000; Singh and Kishore 2004; Molden et al. 2007; Peden et al. 2007; Haileslassie et al. 2009, 2011; Descheemaeker et al. 2010; Peters et al. 2010; Rockström et al. 2010; Moore et al. 2011; de Boer et al. 2012; Zonderland-Thomassen and Ledgard 2012; Krauß et al. 2015). Renault and Wallander (2000) calculated the water productivity of poultry for Californian conditions. Crop transpiration and soil evaporation were considered to be water input. Renault and Wallander (2000) estimate the water productivity of poultry at 0.244 kg m^{-3} water, the water productivity of meat protein at 33 g m^{-3} water, and the water productivity of food energy in poultry at 1.4 MJ m^{-3} water. Chapagain and Hoekstra (2003) estimate the virtual water content of poultry, including crop transpiration, soil evaporation, service, and drinking water, to be between 0.9 and 4.2 m^3 water kg^{-1} poultry. The world average is estimated at 1.5 m^3 kg^{-1} (Chapagain and Hoekstra 2003). The wide range of water productivity or virtual water content is due to the regions investigated and their climatic conditions, the intensity of production and the sources of water included in the water input.

The aim of this study is to quantify the water productivity of poultry production under commercial conditions in Germany and to investigate the influence of different broiler fattening systems. A highly water-productive poultry production system is outlined.

Material and Methods

System boundaries and data

The water productivity of poultry production is analyzed from cradle to farm-gate. The system includes the broiler chicken and the parent stock. The water demand for feed supply, drinking and cleaning was considered here. The indirect water demand for the production of N-fertilizer, supply of diesel and electricity, and the construction of farm buildings was not considered, since this was assumed to be negligible as is reported for milk production (de Boer et al. 2012; Döring et al. 2013).

The most common production and keeping systems in Germany according to the German Agricultural Society (Berk 2008) were investigated. Data on animals per square meter, fattening duration, feed conversion, final weight, and idle time were taken from Berk (2008). Diets were developed according to Jeroch et al. (1999). North-East Germany is considered as the feed production region. Data on feed production conditions were taken from Kraatz (2012).

Fattening systems

Broiler chicken

Various broiler fattening systems are established in Germany. The most common and predominant systems are fast fattening, intermediate fattening, and slow fattening (Berk 2008) (Table 1). A combined system of fast and intermediate fattening is known as splitting fattening. The duration of fattening, the live weight at the end of the fattening, and the carcass weight increase from fast-fattening to slow fattening, while the feed conversion ratio and the stock density decrease (Table 1) (Berk 2008). The live weight of the animals rises with increasing fattening duration from 1.6 kg in 30 days to 3.0 kg in 46 days. The feed

Table 1. Broiler fattening systems according to Berk (2008).

Fattening system	Animals per barn[1]	Fattening period [d]	Final weight [kg]	Carcass weight [kg]	Feed conversion ratio [kg live weight kg^{-1} feed]
Fast fattening	39,900	30	1.6	1.1	0.625
Intermediate fattening	31,000	37	2.1	1.5	0.581
Splitting-fattening total	39,900				
Young[2]	8,900	30	1.6	1.1	0.625
Old[2]	31,000	37	2.1	1.5	0.581
Slow-fattening total	31,000				
Female young[2]	9,300	39	2.0	1.4	0.556
Female old[2]	6,200	46	2.3	1.6	0.556
Male	15,500	46	3.0	2.1	0.556

[1]Barn size of 1700 m^2.

[2]Seven days difference in age of slaughtering between the young and the old animals.

conversion ratio, as ratio of live weight to feed intake, decreases with an increase in fattening duration. All systems are considered under equal conditions with a barn area of 1,700 m^2 and in the keeping of the parent stock. A barn with an area of 1,700 m^2 can accommodate nearly 40,000 broiler chicken, which is a legal limitation for the assessment of environmental effects (Keßler 2012).

The female and male broiler chicken were taken into the barn together in the fast-fattening system and the intermediate-fattening system. The entire stock is removed from the barn on reaching the target live weight.

In the slow-fattening system the males and females are housed separately because of the different daily weight gain. Sixty percent of the females are removed from the barn after 39 days. This gives the remaining females and males more space. One week later they are removed from the barn too.

In the splitting-fattening system 39,900 broiler chicken are taken into the barn as in the fast-fattening system. After 30 days, 22% of the animals are removed from the barn. The remaining 31,000 animals are removed from the barn 1 week later. This procedure is necessary to meet the keeping regulations of a maximum live weight of the animals of 35 kg per square meter of barn.

Parent stock

A standard parent stock is considered uniformly for all fattening systems. The barn of the parent stock has an area of 1,700 m^2 and is equipped like that for laying hens (Mtileni et al. 2007). The barn houses 8,500 females and 850 males (Mtileni et al. 2007). Each hen generates 150 broiler chicken in 64 weeks (Jiang et al. 1998).

Composition and intake of feed

The composition of the feed for the broiler chicken and the parent stock is shown in Table 2. The ingredients are maize grain, rapeseed meal, rapeseed oil, soybean meal, winter barley, and winter wheat. For the longer-duration fattening, the share of protein-rich components decreases while the share of grain increases (Table 3). Protein-rich feed is fed to the fast-fattening, the intermediate-fattening and the splitting-fattening broiler chicken all the time and to the slow-fattening broiler chicken in the first 25 days (Jeroch et al. 1999). A grain-rich feed is fed to the slow-fattening broiler chicken after 25 days up to the end of fattening (Jeroch et al. 1999) (Table 3). The feed of the parent stock contains 85% grain and only 10% soybean meal (Jeroch et al. 1999) (Table 2). The feed intake of the broiler chicken during the fattening period and of the parent stock during the rearing and laying period is shown in Table 3. A laying hen produces 150 broiler chicken and consumes 60 kg feed during the laying period, so the parent stock consume 400 g feed per broiler chicken (Jiang et al. 1998).

Table 2. Composition of the feed according to Jeroch et al. (1999).

	Feed		
	Protein-rich	Grain-rich	Parent
Feedstuff	Composition in %		
Maize grain	31	26	10
Rapeseed meal	4	5	0
Rapeseed oil	5	5	5
Soybean meal	39	23	10
Winter barley	0	11	15
Winter wheat	21	30	60

Calculation of water productivity

Definition of water productivity

Water productivity is generally defined as the relation of useful output to water input (Seckler et al. 2003). In this study, the output is defined on a mass basis, food energy basis, and food protein basis. The dry matter yield of the crops [kg DM] and the carcass weight of the broiler chicken [kg CW] are defined as the mass basis.

The water productivity of the combined feed was calculated by multiplying the share of the combined feed components (Table 2) by the water productivity of the components (Table 5). The water productivity of the feed WP_{feed} [kg DM m^{-3} $W_{\text{input-feed}}$] is defined by the *crop yield* [kg DM] related to the water input $W_{\text{input-feed}}$ [m^3].

Table 3. Feed intake per animal and growing period according to Berk (2008), Jeroch et al. (1999), and Jiang et al. (1998).

	Feed		
	Protein-rich	Grain-rich[1]	Parent
Fattening system	Intake animal^{-1} growing period^{-1} [kg]		
Fast fattening	2.6[2]	–	–
Intermediate fattening	3.6[2]	–	–
Splitting fattening – young	2.6[2]	–	–
Splitting fattening – old	3.6[2]	–	–
Slow fattening – female young	2.0[2,3]	1.6[2,3]	–
Slow fattening – female old	2.0[2,3]	2.1[2,3]	–
Slow fattening – male	2.0[2,3]	3.4[2,3]	–
Parent stock	–	–	60[4]

[1]After 25 days in the slow-fattening system.
[2]Berk (2008).
[3]Jeroch et al. (1999).
[4]Jiang et al. (1998).

$$WP_{\mathrm{feed}} = \text{crop yield}/W_{\mathrm{input-feed}} \quad (1)$$

The water productivity of the poultry meat $WP_{\mathrm{poultry\_meat}}$ [kg CW m^{-3} W_{input}] is defined by the *poultry meat* produced in kg CW per broiler chicken related to the water input W_{input} [m^3].

$$WP_{\mathrm{poultry\_meat}} = \text{poultry meat}/W_{\mathrm{input}} \quad (2)$$

The water productivity of the food energy of poultry meat $WP_{\mathrm{poultry\_energy}}$ [MJ m^{-3} W_{input}] is defined by the *food energy* of poultry meat produced per broiler chicken [MJ] related to the water input W_{input} [m^3]. The food energy content of the carcass is 8.92 MJ kg^{-1} CW (USDA 2013) and the carcass weights are shown in Table 1.

$$WP_{\mathrm{poultry\_energy}} = \text{food energy}/W_{\mathrm{input}} \quad (3)$$

The water productivity of the food protein of poultry meat $WP_{\mathrm{poultry\_protein}}$ [g_{protein} m^{-3} W_{input}] is defined by the *food protein* of poultry meat produced per broiler chicken [g_{protein}] related to the water input W_{input} [m^3]. The food protein content is 183.3 g kg^{-1} CW (USDA 2013) and the carcass weights are shown in Table 1.

$$WP_{\mathrm{poultry\_protein}} = \text{food protein}/W_{\mathrm{input}} \quad (4)$$

Definition of water input

The water input according to Prochnow et al. (2012) includes the transpiration from precipitation, irrigation water, drinking, and process water in the barn and indirect water. Assigning these components of the water input to the steps of poultry production, the water input W_{input} [m^3] consists of the water input for feed production $W_{\mathrm{input\text{-}feed}}$ [m^3], the water supplied by technical means and used in the barn $W_{\mathrm{tech\text{-}barn}}$ [m^3], and the water required for replacement of the broiler chicken $W_{\mathrm{input\text{-}parent}}$ [m^3], which is part of the indirect water demand in prechains:

$$W_{\mathrm{input}} = W_{\mathrm{input-feed}} + W_{\mathrm{tech-barn}} + W_{\mathrm{input-parent}} \quad (5)$$

$W_{\mathrm{input\text{-}feed}}$ [m^3] is the sum of crop transpiration from precipitation $W_{\mathrm{prec\text{-}transp}}$ [m^3] and the irrigation water W_{irri} [m^3]. The whole amount of water used for irrigation W_{irri} is taken into account, and not just that part which is transpired by the plants, as the W_{irri} is taken out of the natural cycle (Prochnow et al. 2012).

$$W_{\mathrm{input-feed}} = W_{\mathrm{prec-transp}} + W_{\mathrm{irri}} \quad (6)$$

$W_{\mathrm{tech\text{-}barn}}$ [m^3] is the sum of the cleaning water $W_{\mathrm{input\text{-}clean}}$ [m^3] and the drinking water of the animals $W_{\mathrm{input\text{-}drink}}$ [m^3].

$$W_{\mathrm{tech-barn}} = W_{\mathrm{input-drink}} + W_{\mathrm{input-clean}} \quad (7)$$

$W_{\mathrm{input\text{-}parent}}$ [m^3] is the sum of $W_{\mathrm{input\text{-}feed\text{-}parent}}$ [m^3] and $W_{\mathrm{tech\text{-}barn\text{-}parent}}$ [m^3].

Calculation of crop transpiration

The water input used for feed production $W_{\mathrm{input\text{-}feed}}$ is calculated according to Krauß et al. (2015) and Prochnow et al. (2012). The actual crop transpiration is calculated by using the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB) Modeling Database (Drastig et al. 2013) on a daily basis, considering the region of North-East Germany and including the years 2008, 2009, and 2010. It is based on the Food and Agriculture Organization of the United Nations (FAO) 56 dual crop coefficient method under nonstandard conditions (Allen et al. 1998) and extended with a module to consider crop water stress and interception loss.

The reference evapotranspiration ET_{O} [mm d^{-1}] is calculated with the FAO Penman-Monteith equation (Allen et al. 1998). Multiplying ET_{O} [mm d^{-1}] by the single crop coefficient K_c [-] determines the potential evaporation of a crop ET_c [mm d^{-1}] (Allen et al. 1998).

$$ET_c = K_c ET_{\mathrm{O}} \quad (8)$$

The crop coefficient K_c [-] is separable in the basal crop coefficient for crop transpiration K_{cb} [-] and a coefficient for soil evaporation K_e [-]. Under optimal wetting conditions of the soil the potential crop transpiration T_c [mm d^{-1}] is calculated by multiplying ET_{O} [mm d^{-1}] by the K_{cb} [-].

$$T_c = K_{cb} ET_{\mathrm{O}} \quad (9)$$

The potential crop transpiration T_c [mm d^{-1}] is multiplied by the transpiration reduction factor K_s [-], which is necessary to consider water stress, to calculate the actual crop transpiration from precipitation $T_{\mathrm{act\text{-}prec}}$ [mm d^{-1}]. The data for plant available water in the 'BÜK 300' (soil overview map, scale 1:300,000, State Office for Mining, Geology and Resources Brandenburg) are used.

$$T_{\mathrm{act-prec}} = K_s K_{cb} ET_{\mathrm{O}} \quad (10)$$

The sum of $T_{\mathrm{act\text{-}prec}}$ [mm d^{-1}] over day d within the reference period is considered as the actual crop transpiration originated from precipitation $W_{\mathrm{prec\text{-}transp}}$ [m^3].

The reference period is the time between the harvest of the previous crop $d = 1$ and the harvest of the main crop m.

$$W_{\mathrm{prec-transp}} = \sum_{d=1}^{m} T_{\mathrm{act-prec}}(d) \tag{11}$$

Winter rye is chosen as previous crop, as it accounts for 40% of all cereals grown in North-East Germany (MIL 2012). The average harvest is on 1. August. The weather data of the weather stations located in North-East Germany are used for the calculation of crop transpiration. The weather stations are run by the German National Meteorological Service (Deutscher Wetterdienst – DWD). For the years 1971 to 2000 the average temperature was 9.0°C and the average rainfall was 553 mm (DWD 2013). For the balance period 2008, 2009, and 2010 the average temperature was 9.2°C and the average rainfall was 659 mm (DWD 2013). The water productivity of soybeans calculated by Prochnow et al. (2012) for Argentine and Brazilian conditions is taken into account, because 70% of the soybeans fed in Germany were grown in Argentina and Brazil (Statistisches Bundesamt [German Federal Statistical Office] 2010).

Feed production

The feed is produced according to good agricultural practice in terms of seeding, harvesting, and fertilization. Four soil groups are predominant in North-East Germany. The predominant soil characteristics and soil types in soil group 1 are clay, loam, and loamy sand. In soil group 2 loamy sand is predominant. Loamy sand and sandy loam are the dominating soil types in soil group 3. The soil in soil group 4 is characterized by sand and loamy sand. The variability of the soil characteristics lead to differences in the potential yield of the land (Table 4). North-East Germany was divided into 20,000 polygons to combine the soil groups and the soil overview map. Rape seed, winter barley, and winter wheat can be cultivated in all soil groups. Maize for grain can be cultivated in soil group 1, 2, and 3. The data of the crop yield are taken from the State Office for Rural Development, Agriculture and Reorganization of Land (LELF 2010). The seed and harvest dates are considered to be the same in all soil groups. Table 4 shows the dry matter yield of the crops in the four soil groups, the seeding date and the harvesting date. The mean WP_{feed} of a single component of the feed is calculated with the weighted average over the four soil groups within one crop. The water productivity of the combined feed was calculated by multiplying the share of the combined feed components (Table 2) by the water productivity of the components (Table 5).

Table 4. Dry matter yield (LELF 2010), seeding date, and harvesting date (good agricultural practice) of the crops for the soil groups.

Crop	Dry matter yield in t ha^{-1} a^{-1} in soil group				Seeding date	Harvesting date
	1	2	3	4		
Maize grain	6.9	6.0	5.2	–	20. April	20. October
Winter barley	6.0	5.2	4.1	3.1	15. September	14. July
Winter rapeseed	3.8	3.3	2.7	2.0	25. August	27. July
Winter wheat	6.5	5.4	4.3	3.3	5. October	5. August

Technical water in the barn

Components

The water provided by technical means used in the barn $W_{\mathrm{tech\text{-}barn}}$ [m^3] includes the drinking water for the animals, cleaning water for the barn, the hygiene lock, and the washing machine.

Drinking water

The cumulative drinking water demand per broiler chicken ($W_{\mathrm{input\text{-}drink\text{-}broiler}}$) [m^3] is calculated according to KTBL (2009) as a function of age in weeks x:

$$W_{\mathrm{input-drink-broiler}} = 0.00042x^{1.623} \tag{12}$$

The drinking water demand of the parent stock ($W_{\mathrm{input\text{-}drink\text{-}parent}}$) is considered at 0.3 L $W_{\mathrm{input\text{-}drink\text{-}parent}}$ day^{-1} animal^{-1} (KTBL 2009).

Cleaning water

The cleaning water demand ($W_{\mathrm{input\text{-}clean}}$) of the barn for the broiler chicken and the parent stock comprises water for soaking, cleaning, and disinfection and amounts to 24.4 L $W_{\mathrm{input\text{-}clean}}$ m^{-2} (KTBL 2009). The hygiene lock and the washing machine for the workwear require 50 L $W_{\mathrm{input\text{-}clean}}$ day^{-1} (KTBL 2009).

Results and Discussion

Water productivity of the feed

The water productivity of the feedstuffs is shown in Table 5. Maize grain has the highest water productivity with 1.8 kg dry matter (DM) m^{-3} $W_{\mathrm{input\text{-}feed}}$, while the water productivity is lowest for soybean meal with 0.4 kg DM m^{-3} $W_{\mathrm{input\text{-}feed}}$ and rapeseed meal with 0.8 kg DM m^{-3} $W_{\mathrm{input\text{-}feed}}$. Winter wheat and winter

Table 5. Water input and water productivity of the feedstuffs for the soil groups according to Krauß et al. (2015) (values in brackets are the standard deviation).

	Soil group				
Feedstuff	Mean[1]	1	2	3	4
Water input [m^3 $W_{input\text{-}feed}$ ha^{-1}]					
Maize grain	3,200 (±480)	3,570 (±410)	3,230 (±450)	3,140 (±470)	–
Winter barley	3,030 (±300)	3,090 (±270)	3,040 (±280)	3,020 (±290)	3,040 (±320)
Winter rapeseed	3,360 (±260)	3,340 (±240)	3,340 (±240)	3,350 (±250)	3,370 (±270)
Winter wheat	3,920 (±330)	4,000 (±270)	3,950 (±280)	3,910 (±320)	3,910 (±360)
Water productivity [kg DM m^{-3} $W_{input\text{-}feed}$]					
Maize grain	1.8 (±0.3)	2.0 (±0.3)	1.9 (±0.3)	1.7 (±0.2)	–
Soybean meal[2]	0.4	–	–	–	–
Winter barley	1.3 (±0.3)	2.0 (±0.2)	1.7 (±0.2)	1.4 (±0.1)	1.0 (±0.1)
Winter rapeseed meal	0.8 (±0.2)	1.1 (±0.1)	1.0 (±0.1)	0.8 (±0.1)	0.6 (±0.0)
Winter wheat	1.1 (±0.2)	1.6 (±0.1)	1.4 (±0.1)	1.1 (±0.1)	0.8 (±0.1)

[1]Weighted average.
[2]Prochnow et al. 2012.

barley have a medium water productivity of 1.1 and 1.3 kg DM m^{-3} $W_{input\text{-}feed}$. The water productivity of the feed decreases with a decreasing yield potential of the soil groups, reflected by the increasing share of sand in the soil. The variation of the water productivity between the soil groups was caused by the differing yields, while the transpiration of the plants was similar.

Prochnow et al. (2012) calculated the average water productivity of barley, rapeseed meal, and wheat of a commercial farm in East Germany, obtaining nearly the same results. Barley had a water productivity of 1.4 kg DM m^{-3} $W_{input\text{-}feed}$ with a minimum of 0.8 and a maximum of 1.9. Rapeseed had a water productivity of 0.8 kg DM m^{-3} $W_{input\text{-}feed}$ with a minimum of 0.6 and a maximum of 1.0. Wheat had a water productivity of 1.1 kg DM m^{-3} $W_{input\text{-}feed}$ with a minimum of 0.7 and a maximum of 2.0. The variation between the water productivity of the different fields on the commercial farm was as high as the variation between the soil groups.

The variation between the water productivity of the crops is caused by the different crop yields and crop transpiration. The average water input for maize grain, barley, rapeseed, and wheat is 3,200, 3,030, 3,360, and 3,920 m^3 ha^{-1}, respectively (Table 5). Among the crops regarded, the transpiration of maize grain shows the second lowest value, while its yield is highest. This results in the highest water productivity for maize. By comparison with the winter wheat, the winter barley transpires more than 20% less water, while its yield is only 5% less. Therefore, the water productivity of barley is higher compared with wheat.

The water productivity of the combined feed in the fattening systems is 0.7 kg DM m^{-3} $W_{input\text{-}feed}$ for the protein-rich feed of the fast-fattening broiler chicken, 0.8 kg DM m^{-3} $W_{input\text{-}feed}$ for the grain-rich feed and 1.0 kg DM m^{-3} $W_{input\text{-}feed}$ for the parent feed. The protein-rich feed contains a higher share of protein from soybean meal than the grain-rich feed. The grain-rich feed contains more winter barley and winter wheat. The water productivity of grain is higher than that of soybean meal and so the protein-rich feed has lower water productivity than the grain-rich feed. The parent feed contains only 10% soybean meal and for that reason the water productivity of the parent feed is highest compared with the other feeds.

Water use of the parent stock

The water input for feed production of the parent stock is 0.365 m^3 per broiler chicken. The drinking water and the water used for cleaning the barn of the parent stock is 1 L per broiler chicken. In total 0.366 m^3 water per broiler chicken is used to produce the feed, to provide drinking water and to clean the barn of the parent stock.

Water input, product output and water productivity of the broiler chicken

The water input of the broiler fattening systems is shown in Table 6. The water input for feed production increases with an increasing duration of fattening from 3.2 m^3 $animal^{-1}$ for fast fattening to 6.0 m^3 $animal^{-1}$ for the males in slow fattening. The water input for feed production accounts for 90 to 93% of the whole water input. The water used for the parent stock accounts for 7 to 10% of the water input. The water used for cleaning the barn and for the hygiene lock is 44 m^3 per fattening period and accounts for less than 1% of total water input.

Table 6. Water use, product output, and water productivity of the fattening systems.

		Fattening system									
				Splitting fattening			Slow fattening				
		Fast fattening	Intermediate fattening	Young[2]	Old[2]	Total	Female young[2]	Female old[2]	Male	Total	Parent[1]
Water input											
$W_{input\text{-}feed}$[3]	m^3 $broiler^{-1}$	3.2	4.5	3.2	4.5		4.2	4.7	6.0		0.365
$W_{input\text{-}drink}$	m^3 $broiler^{-1}$	0.004	0.006	0.004	0.006		0.007	0.009	0.009		0.001
$W_{input\text{-}parent}$	m^3 $broiler^{-1}$	0.366	0.366	0.366	0.366		0.366	0.366	0.366		
$W_{input\text{-}feed}$	m^3 $barn^{-1}$	128,509	138,246	28,665	138,246	166,911	38,637	29,007	93,636	161,279	464,933
$W_{input\text{-}drink}$	m^3 $barn^{-1}$	178	194	40	194	234	63	55	138	257	1,382
$W_{input\text{-}clean}$	m^3 $barn^{-1}$	44	44			44				44	65
total W_{input}[4]	m^3 $barn^{-1}$	143,322	149,821			181,780				172,918	466,380
Output											
Animals per barn		39,900	31,000	8,900	31,000	39,900	9,300	6,200	15,500	31,000	9,350
Carcass weight	kg $broiler^{-1}$	1.1	1.5	1.1	1.5		1.4	1.6	2.1		
Mass output	kg CW[5] $barn^{-1}$	44,688	45,570			55,538				55,552	
Food energy content	MJ kg^{-1} CW	8.92	8.92			8.92				8.92	
Food energy output	MJ $barn^{-1}$	398,617	406,484			495,399				495,524	
Food protein content	$g_{protein}$ kg^{-1} CW	183.3	183.3			183.3				183.3	
Food protein output	kg $barn^{-1}$	8,191	8,353			10,180				10,183	
Water productivity											
$WP_{poultry\_meat}$[6]	kg CW m^{-3} W_{input}	0.3	0.3			0.3				0.3	
$WP_{poultry\_energy}$[7]	MJ m^{-3} W_{input}	2.8	2.7			2.7				2.9	
$WP_{poultry\_protein}$[8]	$g_{protein}$ m^{-3} W_{input}	57	56			56				59	

[1]The values per broiler represent the water input per broiler chicken. The values per barn represent the water input of the parent barn.
[2]Seven days difference in age of slaughtering between the young and the old animals (see Table 1).
[3]$W_{input\text{-}feed}$ is calculated by multiplying the water productivity of the combined feed by the feed intake.
[4]Total $W_{input} = W_{input\text{-}feed} + W_{input\text{-}drink} + W_{input\text{-}clean}$ per barn + ($W_{input\text{-}parent}$ * animals per barn).
[5]CW = carcass weight.
[6]$WP_{poultry\_meat}$ = total W_{input}/Mass output.
[7]$WP_{poultry\_energy}$ = total W_{input}/Feed energy output.
[8]$WP_{poultry\_protein}$ = total W_{input}/Feed protein output.

The live weight and the carcass weight of the animals increase with increasing fattening duration and feed intake. The food energy and food protein content of the carcass is given as equal between the fattening systems (Table 6). Hence, the output of food energy and food protein increases with an increasing live weight and carcass weight.

The water productivity of poultry meat is 0.3 kg carcass weight m^{-3} water input in all fattening systems (Table 6). Water productivity in terms of food energy and food protein varies slightly between the fattening systems. The water productivity of food energy in the broiler chicken reared in the intermediate-fattening and splitting-fattening systems is the lowest in this study. The water productivity of food energy in the fast-fattening and the slow-fattening systems is slightly higher than in the other fattening management systems.

Peden et al. (2007) and Singh et al. (2003) also identified the production of feed as the main contributor to water input in animal production. The nearly equal water productivities in the different fattening systems can be explained by the opposing effects of fattening intensity on feed requirement on the one hand and the water productivity of the diets and carcass weight on the other. The broiler chicken with a shorter fattening period has a lower feed demand and a higher feed conversion ratio than animals with a longer fattening period. In fast fattening, the feed conversion ratio is 1.6 kg feed kg^{-1} live weight, and in slow fattening it is 1.8 kg feed kg^{-1} live weight (Berk 2008). The live weight gain of young broiler chicken is mostly generated by the gain in protein. With increasing age the demand for protein related to energy decreases. In fast fattening the animals were fed solely with protein-rich feed, characterized by low water productivity. The lower feed conversion ratio of the animals in slow fattening is compensated by the higher water productivity of the feed, which results in equal water productivity for the poultry meat of all fattening systems.

The water productivity of the poultry meat is 20% higher than that estimated by Renault and Wallander (2000), who – in contrast to this study – included soil evaporation in addition to crop transpiration and excluded the water use in the barn and the water use of the parent stock. Chapagain and Hoekstra (2003) estimated the virtual water content for poultry considering plant transpiration, soil evaporation, and water for drinking and servicing, but excluding the water use of the parent stock. However, calculating the inverse proportion of the virtual water content to have the same unit as the water productivity, the water productivity in this study would be 40% lower than that estimated by Chapagain and Hoekstra (2003) for a system equivalent to fast fattening. The diets of the broiler chicken contained more wheat and maize grain instead of soybean meal (Chapagain and Hoekstra 2003) and are comparable with the parent feed. The average daily gain is 45% lower than in this study. However, the feed conversion ratio is 20% higher. As described before, wheat and maize grain have higher water productivity than soybean meal. The higher feed conversion ratio also increases the water productivity significantly. The longer fattening period increases the drinking and service water demand, which plays a minor part in water input (Singh et al. 2003 and Peden et al. 2007).

In this study, the food energy-related water productivity of the slow-fattening system was 2.9 MJ m^{-3} water (Table 6), which is twice than calculated by Renault and Wallander (2000). The main reason for this difference is the energy content of the carcass, which is 35% higher than that assumed by Renault and Wallander (2000). Assuming an equal energy content results in a water productivity difference of less than 10%. Similarly, the protein-related water productivity is 70% higher than that estimated by Renault and Wallander (2000), since the assumed protein content of poultry meat is 40% higher than that in the study of Renault and Wallander (2000).

The fattening systems investigated do not differ in terms of water productivity. Hence, modifying the intensity of fattening is no approach for increasing the water productivity in broiler production. As at least 90% of the water input originates in feed production, options for increasing the water productivity must be sought in cultivation of the feed crops, optimizing the diets with regard to water-productive crops and a performance-linked amino acid pattern, and improvements in breeding to increase feed conversion ratios.

Conclusions

The major share of the water input in poultry production is caused by feed production. The production intensity of the fattening systems does not affect the water productivity in poultry production. The higher water input in slower fattening systems is compensated by the higher output of mass, food energy, and food protein.

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Conflict of Interest

None declared.

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Graphical Abstract

The contents of this page will be used as part of the graphical abstract of html only. It will not be published as part of main.

Fattening system	Animals per barn[1]	Fattening period [d]	Final weight [kg]	Carcass weight [kg]	Feed conversion ratio [kg live weight kg^{-1} feed]
Fast fattening	39,900	30	1.6	1.1	0.625
Intermediate fattening	31,000	37	2.1	1.5	0.581
Splitting-fattening total	39,900				
Young[2]	8,900	30	1.6	1.1	0.625
Old[2]	31,000	37	2.1	1.5	0.581
Slow-fattening total	31,000				
Female young[2]	9,300	39	2.0	1.4	0.556
Female old[2]	6,200	46	2.3	1.6	0.556
Male	15,500	46	3.0	2.1	0.556

[1]Barn size of 1700 m^2.
[2]Seven days difference in age of slaughtering between the young and the old animals.

Four fattening systems were analyzed in terms of water use for feed production, drinking, cleaning and the parent stock. In all fattening systems the water input for feed production accounted for more than 90% of the total water input. For all fattening systems the water productivity was 0.3 kg carcass weight per m^3 water input, 2.8 MJ food energy per m^3 water input and 57 g food protein per m^3 water input. The shorter fattening period and lower feed demand in the more intensive fattening systems were juxtaposed to the higher carcass weight and higher water productivity of the feed components in the more extensive systems.

Annex C: Krauß, M.; Drastig, K.; Prochnow, A.; Rose-Meierhöfer, S.; Kraatz, S. (2016): Drinking and cleaning water use in a dairy cow barn. Water 8, 302-317.

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Article

Drinking and Cleaning Water Use in a Dairy Cow Barn

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Abstract: Water is used in dairy farming for producing feed, watering the animals, and cleaning and disinfecting barns and equipment. The objective of this study was to investigate the drinking and cleaning water use in a dairy cow barn. The water use was measured on a well-managed commercial dairy farm in North-East Germany. Thirty-eight water meters were installed in a barn with 176 cows and two milking systems (an automatic milking system and a herringbone parlour). Their counts were logged hourly over 806 days. On average, the cows in the automatic milking system used 91.1 (SD 14.3) L drinking water per cow per day, while those in the herringbone parlour used 54.4 (SD 5.3) L per cow per day. The cows drink most of the water during the hours of (natural and artificial) light in the barn. Previously published regression functions of drinking water intake of the cows were reviewed and a new regression function based on the ambient temperature and the milk yield was developed (drinking water intake (L per cow per day) = −27.937 + 0.49 × mean temperature + 3.15 × milk yield (R^2 = 0.67)). The cleaning water demand had a mean of 28.6 (SD 14.8) L per cow per day in the automatic milking system, and a mean of 33.8 (SD 14.1) L per cow per day in the herringbone parlour. These findings show that the total technical water use in the barn makes only a minor contribution to water use in dairy farming compared with the water use for feed production.

Keywords: drinking water; cleaning water; disinfection; automatic milking system; herringbone parlour

1. Introduction

Water is used in dairy farming for producing feed crops, processing feed, watering the animals, cleaning and disinfecting the barn and equipment, and cooling the milk and the barn. Cultivation of feed crops accounts for the highest share of water use in dairy farming [1–5]. In rainfed farming, this water is provided by the natural water cycle. Access to precipitation is assured by the access to the land and does not lead to additional costs [6]. The water used in the barn is mainly provided by technical means and represents part of the technical water [6]. This technical water accounts for less than 5% of total water use in German dairy farming [2], but it is diverted from its natural cycle and so must be paid for. Hence particular attention is paid to the use of technical water. The amount of technical water used in barns depends on the equipment and management of the dairy farm.

Several studies have investigated water use for drinking, cleaning, and disinfection. The drinking water demand of lactating cows has been investigated by several authors, including Cardot et al. [7], Holter and Urban [8], Meyer et al. [9], and Murphy et al. [10]. All authors estimated the daily drinking water intake of cows depended on influencing factors such as the milk yield of the cows, live weight, dry matter content of the feed, dry matter intake, day of the year, rainfall, temperature, and sodium intake. Not all authors used the same variables to estimate drinking water intake. Some of the variables were dependent on each other; for example, the dry matter intake depended on the live weight of the animals, and the milk yield on the dry matter intake. Including the day of the year in the estimation [8] should indicate the temperature change during the year, while Meyer et al. [9] and Murphy et al. [10] included the mean or the minimum temperature. The investigations were conducted for cows in early to mid-lactation and covered a period of at most 16 weeks.

Scientific investigations of the cleaning water demand in the barn are scarce [11]. The cleaning water demand has mainly been investigated by public authorities and consulting agencies [12–17], and the available studies do not describe in detail how the cleaning water demand was measured and estimated. Water for cleaning in the dairy barn is used for different situations, including for the process of milking, which requires cleaning and disinfection of the milking equipment, the milking parlour, and the milk cooling tank. Cleaning the equipment and cooling tank is computer-controlled, so the water needs are constant within the same system. However, different systems are available, such as hot water cleaning and circulation cleaning. The cleaning water demand of the milking parlour depends on the area, the worker, the system, and the farm management. For example, a high-pressure cleaner needs less water than a hose. Sometimes less water could be used to achieve the same cleaning result, but workers are urged to use more water because the additional water is needed to keep slurry pumpable. Hence, without information on the methods used to measure and estimate the cleaning water demand, application to a specific barn remains uncertain.

The aim of this study was to investigate the technical water use in a dairy cow barn on a commercial dairy farm in North-East Germany by taking detailed measurements of the drinking and cleaning water demand over a period of two years. Regression functions of the drinking water demand over the whole lactation cycle were developed and compared with existing regression functions and methods to test the equations for their accuracy. Two milking systems were compared with respect to technical water demand per cow, kg milk, and milking. Daily and annual variations in the water demand are displayed for groups of cows with different milk yields. Understanding of how much cleaning water is used is improved. Detailed portioning of the cleaning water demand to the main contributors is outlined and recommendations to reduce the water use are given.

2. Materials and Methods

2.1. Milking Systems

The dairy farm investigated is located in North-East Germany and manages 675 ha arable land. The farm keeps on average 210 milking cows and 180 calves and heifers. The dairy cow barn is 70 m long and 30 m wide. Two milking systems are established on the farm—an automatic milking system (AMS) with two single boxes and a 2 × 7 herringbone milking parlour (HBP). A group of cows is associated with each milking system, but the cows are moved between the systems during lactation depending on their milk yield and the milking intensity: for the first two weeks after calving, the cows are milked in the HBP; between the 15th and 170th day in milk, they are milked in the AMS; and after the 170th day in milk until the end of lactation, they are milked in the HBP again. The milk yield is recorded at each milking for every cow in the AMS. The two single boxes of the AMS have an area of 35 m^2 and are cleaned with a hose. For the milk yield of the cows in the HBP, the data of the monthly milk performance testing was taken into account. The HBP has an area of 70 m^2 and is cleaned with a hose and a high-pressure cleaner. The milk is collected by a milk truck every two days. The milk tanks are cleaned automatically after emptying.

The cows in the AMS group were fed a total mixed ration of 5.3% alfalfa silage, 22.3% grass silage, 50.0% maize silage, 1.2% straw, 8.4% rape seed meal, 3.9% soy bean meal, 7.7% concentrate (DEUKA MK 204), and 1.2% minerals and vitamins, providing a dry matter intake of 23 kg per cow per day with a dry matter content of 39.8%. The cows in the HBP group were fed a total mixed ratio of 45.2% grass silage, 47.5% maize silage, 6.1% rape seed meal, and 1.2% minerals and vitamins, providing a dry matter intake of 17.4 kg per cow per day with a dry matter content of 35%. The composition, dry matter intake, and dry matter content of each diet was ruminant appropriate, being similar to those reported by Krauß et al. [2].

2.2. Water Metering

To investigate the technical water use of lactating cows in the barn of the commercial dairy farm, 38 water meters (Itron Inc.; Liberty Lake, Washington, WA, USA) were installed at various points of water withdrawal on 23 February 2012. The water withdrawal was measured in as much detail as the installation of the water pipes allowed over a period of more than two years, up to 08 May 2014. The water meters were chosen based on the expected flow rates and pipe diameters, to minimize any flow-rate-dependent measuring inaccuracies. This was important, as there were differences between the readings of the water meters in the pipe and the water meters at the points of withdrawal from the pipe—these differences may have resulted from measurement inaccuracies of the water meters or leakage from the pipe, but the latter was assumed here since it was not possible to distinguish between these effects. Complete datasets are available for 802 of the 806 days. Four datasets were excluded from the analyses because of missing values of the water meters.

A ground plan of the barn and the drinking troughs is shown in Figure 1. The cows in the AMS-group were in the right part of the barn and the cows in the HBP-group were in the left part of the barn. The water was supplied by a single bore and its quality was checked by the farm management; the drinking water was proven to be of a quality suitable for human consumption. The main pipe had a water meter and was split into six smaller pipes. Four of the pipes supplied the drinking troughs, one the AMS, and one the milk tank room. Each group of cows had access to five drinking troughs, and water meters were installed in front of the troughs. Troughs 1, 2, 3 and 4 were supplied by pipe 1. Troughs 5 and 6 were supplied by pipe 2. Troughs 7 and 8 were supplied by pipe 3. Troughs 9 and 10 were supplied by pipe 4. Every pipe had a water tap for drawing cleaning water as well as a water meter for calculating use of cleaning water and detecting leaks. The cleaning water demand of the milking system, the milk tank of the HBP, and the milk tank of the AMS was measured using three hot water meters and three cold water meters. The high pressure cleaner and the hose in the HBP each had a water meter to measure the water use for cleaning the surface of the HBP. The udder brush had a hot water meter and a cold water meter, and the disinfection of the milking units had its own water meter. A hot water meter and a cold water meter were installed in each AMS box. Pipe 5 supplied these four water meters and had its own water meter to detect leaks. In the milk tank room, four water meters were installed to measure the use of cleaning water for the floor of the milk tank room, the milk churn, the workers' hands, and their workwear.

The water meters transmitted their count wirelessly to a collector every hour. The collector transmitted the counts daily to an access point and this transmitted the data to a file transfer protocol (FTP) server. The drinking water intake of the cows and the cleaning water demand of the milk tank, the milking system, and the surface of the milking parlour were measured separately for each group. There was also nonspecific withdrawal which cannot be allocated to one of the milking systems, such as water used for cleaning the floor of the milk tank room, the milk cans, and the workers' clothes.

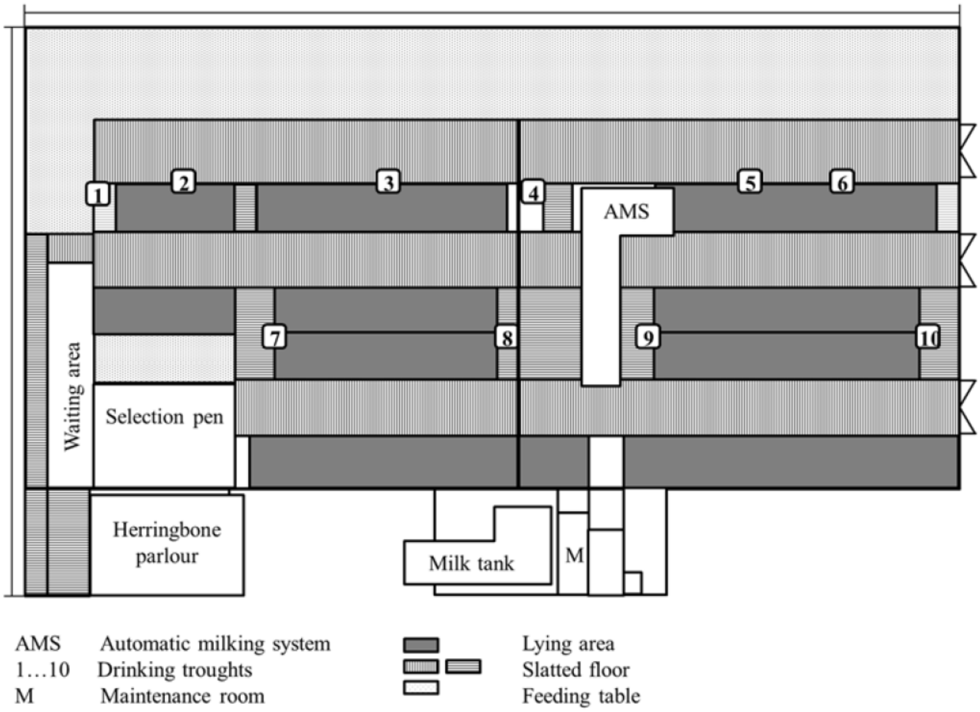

Figure 1. Plan of the dairy barn with milking systems and drinking troughs.

2.3. Technical Water

The term "technical water" is used in the calculation of water use indicators at farm scale [6]. Technical water W_{tech} (m^3) means the water that is provided by technical means in contrast to water which reaches the farm via precipitation, surface, or subsurface flows. W_{tech} (m^3) is subdivided at farm scale into irrigation water W_{irri} (m^3) and tap water W_{tap} (m^3) [6]. In this study the technical water use focuses on water use in the dairy barn $W_{\text{tech-barn}}$ (m^3). $W_{\text{tech-barn}}$ (m^3) can be split into the drinking water demand of the cows $W_{\text{drink-cow}}$ (m^3) and the cleaning water demand W_{clean} (m^3) [3].

2.4. Regression Functions of the Drinking Water Demand

The measurements of drinking water intake on the commercial farm in North-East Germany were compared with the following regression functions from literature [7–10]:

$$\begin{aligned} W_{\text{drink-cow\_daily}} = {} & -26.65 + 1.54 \times \text{DMI} + 1.33 \times Y_{\text{milk}} + 0.89 \times \text{DMC} + 0.58 \times T_{\min} \\ & - 0.30 \times \text{RF} \quad \left(R^2 = 0.45\right) \end{aligned} \tag{1}$$

$$\begin{aligned} W_{\text{drink-cow\_daily}} = {} & -32.39 + 2.47 \times \text{DMI} + 0.6007 \times Y_{\text{milk}} + 0.6205 \times \text{DMC} + 0.0911 \\ & \times \text{DOY} - 0.000257 \times \text{DOY}^2 \quad \left(R^2 = 0.69\right) \end{aligned} \tag{2}$$

$$\begin{aligned} W_{\text{drink-cow\_daily}} = {} & -26.12 + 1.516 \times T_{\text{mean}} + 1.299 \times Y_{\text{milk}} + 0.0058 \times \text{m}_{\text{b}} + 0.406 \times \text{In}_{\text{Na}} \\ & \left(R^2 = 0.60\right) \end{aligned} \tag{3}$$

$$\begin{aligned} W_{\text{drink-cow\_daily}} = {} & 15.99 + 1.58 \times \text{DMI} + 0.90 \times Y_{\text{milk}} + 0.05 \times \text{In}_{\text{Na}} + 1.20 \times T_{\min} \\ & \left(R^2 = 0.59\right) \end{aligned} \tag{4}$$

where the daily drinking water intake of cows is $W_{\text{drink-cow\_daily}}$ ($\text{L} \cdot \text{day}^{-1}$), the milk yield of the cows Y_{milk} ($\text{kg} \cdot \text{day}^{-1}$), the live weight of the animals m_{b} (kg), the dry matter content of the feed DMC (%), the dry matter intake DMI (kg), day of the year DOY (–), rainfall RF ($\text{mm} \cdot \text{day}^{-1}$), mean ambient temperature T_{mean} (°C), minimum ambient temperature $T_{\min}$ (°C), and sodium intake In_{Na} ($\text{g} \cdot \text{day}^{-1}$).

The mean, minimum and maximum temperature and the rainfall were measured by the nearest station (19 km) of the German Meteorological Service and provided by the ATB-Modeling Database [18].

2.5. Statistical Analyses

The hourly data of the water meters and the milk yield data of the cows were checked for completeness. Outliers in the drinking water dataset were eliminated if the values were higher than the threshold of 1.96 × SD [19]. By contrast, outliers in the cleaning water dataset were not eliminated because various factors within a farmstead could legitimately result in these higher values.

The data were analyzed with the software SAS 9.4 (SAS Institute Inc., Cary, NC, USA) and the procedure Proc MEANS to obtain the mean values and standard deviations (SDs). The regression function of the daily drinking water intake was estimated using Proc REG, with the average daily mean temperature and the daily milk yield included as independent variables. The means of the regression functions obtained by Cardot et al. [7], Holter and Urban [8], Meyer et al. [9] and Murphy et al. [10] were compared with the measured values from this study using Proc TTEST.

The performances of the previously published regression functions and the function developed in this study were evaluated by comparing the measured and modeled daily drinking water demands. An ordinary parametric least squares linear regression test with the coefficient of determination (R^2) was used to assess the goodness of fit [19]. In addition, the Nash-Sutcliffe efficiency (NSE), logarithmic Nash-Sutcliffe efficiency (NSElog), Root mean square error (RMSE), ratio of the root mean square error to the standard deviation of measured data (RSR) and percent BIAS (PBIAS), were used for model evaluation following Moriasi [20], Ellis et al. [21], and Tedeschi [22].

3. Results and Discussion

3.1. Drinking Water Demand

The daily drinking water intake per cow throughout the observation period is shown in Figure 2. The drinking water demand of the cows in the AMS showed a seasonal response, being highest in the summer and lowest in the winter. This corresponds with the changes of the daily mean air temperature during the year (Figure 3). Cardot et al. [7], Holter and Urban [8], Meyer et al. [9] and Murphy et al. [10] also identified the drinking water intake as dependent on the temperature or season. The drinking water intake of the cows in the HBP did not show such a seasonal response. Since the group of cows in the HBP was more heterogeneous than in the AMS, the effects of temperature on drinking water intake may have been leveled out.

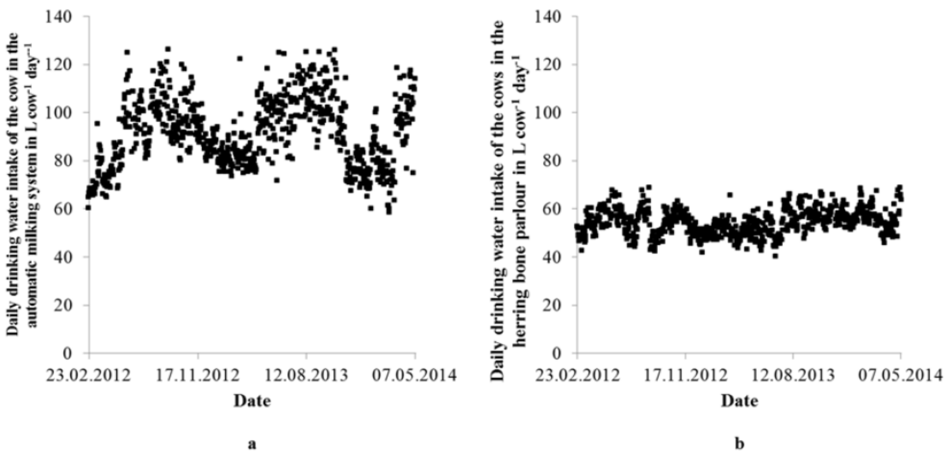

Figure 2. Daily drinking water intake per cow in the (**a**) automatic milking system (AMS) and (**b**) herringbone parlour (HBP).

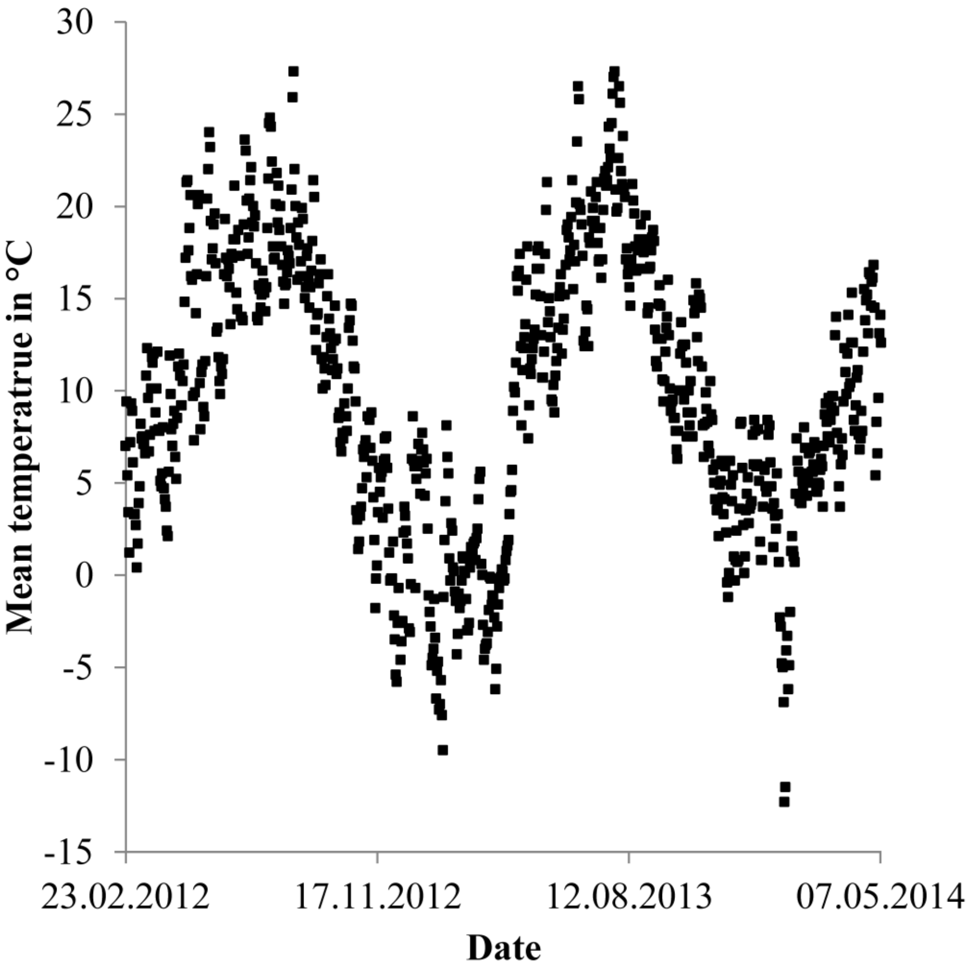

Figure 3. Mean daily air temperature in the observation period.

The drinking water intake changed not only over the year, but also during the day (Figure 4). Between 05:00 and 21:00 h the cows drink 80% of their daily water intake. During this time the workers were in the barn and it was lit. The peak of drinking water intake was observed between 07:00 and 08:00 h for the cows in the AMS, and between 07:00 and 08:00 h and between 17:00 and 18:00 h for the cows in the HBP. This was expected, since the cows in the HBP were milked at these times, and cows drink large amounts of water after milking [7].

The milk yields were needed to calculate the drinking water demand per kg milk and to assess the accuracy of the available regression functions for estimating the drinking water demand of dairy cows. Milk yields are shown in Figure 5 and Table 1. The average milk yield of the 88 cows milked in the AMS was 35.5 kg milk per cow per day, with an average of 2.8 milkings per day and 12.7 kg milk per milking. On average, 92 cows were milked twice per day in the HBP, with an average milk yield of 25.4 kg milk per cow per day or 12.7 kg per milking. Figure 5 is more detailed for the AMS, as milk yield data was available for each milking in contrast to the data for milk yield in the HBP.

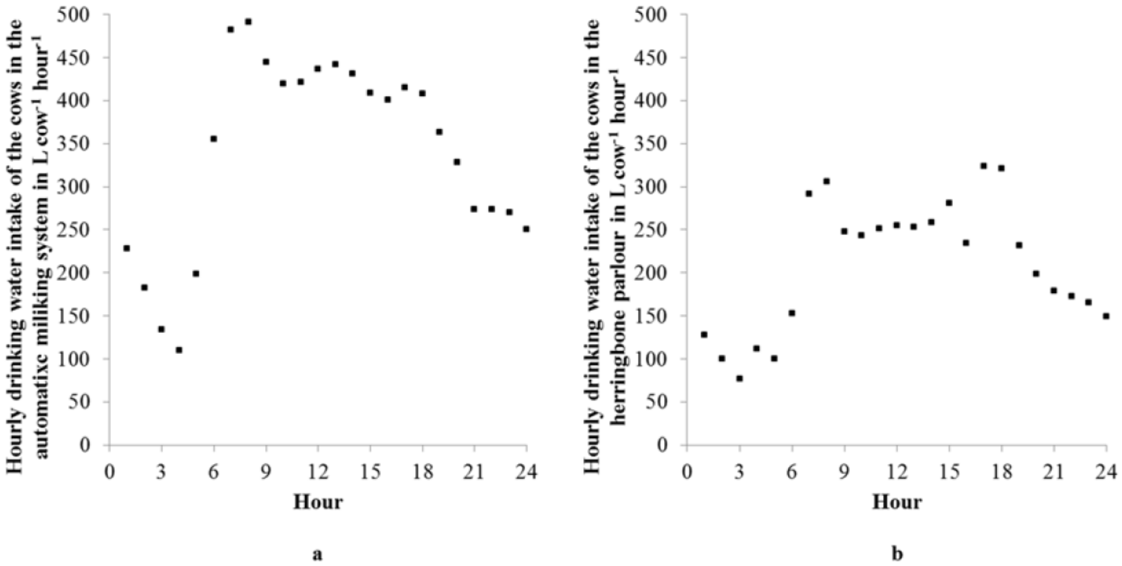

Figure 4. Hourly drinking water intake over the observation period in the (**a**) automatic milking system (AMS) and (**b**) herringbone parlour (HBP) (mean of 802 observation days).

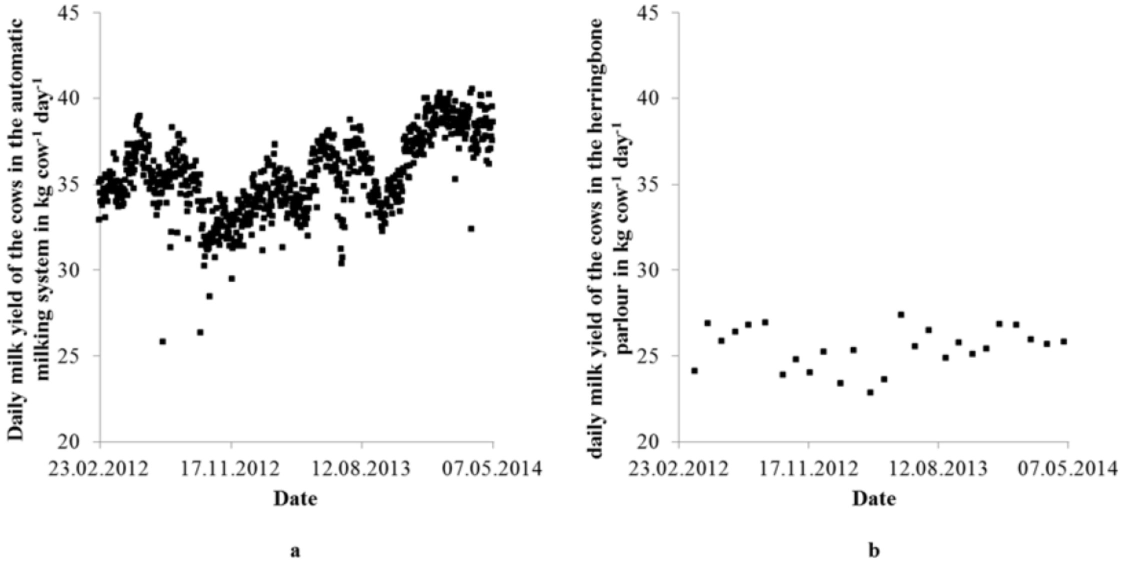

Figure 5. Daily milk yield per cow in the (**a**) automatic milking system (AMS); and (**b**) herringbone parlour (HBP).

Table 1. Milk yield, measured and estimated drinking water intake of the cows.

Measured or Estimated Value	Mean	SD [1]	Min [2]	Max [3]
Automatic milking system				
Number of cows	87.9	4.0	78.0	101.0
Milk yield (kg· cow^{-1}· day^{-1})	35.5	9.6	0.0	83.9
Daily drinking water intake (L· cow^{-1}· day^{-1})				
own measurements	91.1	14.3	58.5	126.2
calculated according to Cardot et al. [7]	95.7 [4]	4.9	82.2	108.4
calculated according to Holter and Urban [8]	76.3 [4]	2.8	68.5	81.1
calculated according to Meyer et al. [9]	84.2 [4]	12.9	51.9	114.2
calculated according to Murphy et al. [10]	92.8	8.1	69.2	113.2
Herringbone milking parlour (HBP)				
Number of cows	91.8	6.2	73.0	101.0
Milk yield (kg· cow^{-1}· day^{-1})	25.4	7.5	2.9	65.3
Daily drinking water intake (L· cow^{-1}· day^{-1})				
own measurements	54.4	5.3	40.2	121.7
calculated according to Cardot et al. [7]	69.2 [4]	4.6	55.6	81.0
calculated according to Holter and Urban [8]	53.0 [4]	2.7	46.5	56.9
calculated according to Meyer et al. [9]	68.9 [4]	12.1	36.7	97.9
calculated according to Murphy et al. [10]	74.4 [4]	8.4	49.2	95.2

Notes: [1] standard deviation; [2] minimum; [3] maximum; [4] significant difference to own measurements ($p \leqslant 0.001$).

The 88 cows in the AMS group drink on average 8.0 m^3 of water per day. This is equivalent to 91.1 L water per cow per day, or 2.6 L per kg milk. Holter and Urban [8] suggested a rule of thumb of 2 L drinking water per kg milk, which is 77% lower than the measured value. The diet provided 34.8 L water, which represented 27% of the total water intake. The calculation of the drinking water demand according to Meyer et al. [9] leads to an underestimation of the drinking water demand by 6.9 L per day, and according to Holter and Urban [8] to an underestimation by 14.8 L per day, while using the regression function of Cardot et al. [7] the drinking water demand was overestimated by 4.6 L per day. The difference between the measured minimum and maximum water intake is 67.7 L per day, while the range of estimated values includes 26 L [7], 13 L [8], 62 L [9] and 44 L [10].

The 92 cows in the HBP group drank on average 5.0 m^3 of water per day, representing a mean drinking water demand of 54.4 L water per cow per day or 2.1 L per kg milk. This was 10% more than Holter and Urban's [8] rule of thumb. The diet provided 32 L water, which was 36% of the total water intake.

The measured drinking water demand of the cows in the AMS and the HBP, the *milk yield of the cows* (kg· cow^{-1}· day^{-1}) and the *mean temperature* (°C) were used to develop a new regression function for the modeling of the daily drinking water demand of cows in the barn ($W_{\text{drink-cow\_daily}}$):

$$W_{drink-cow\_daily} = -27.93 + 0.49 \times mean\ temperature + 3.15 \times milk\ yield \ \left(R^2 = 0.67\right) \quad (5)$$

A comparison of the measured and modeled daily drinking water demand is provided in Table 2. It was found that the function developed in this study was closest to the perfect slope of 1, while the function of Meyer et al. [9] had the smallest y-intercept. A slope of 1 and a y-intercept of 0, using standard regression, indicate that the model perfectly fits the measured data [23]. The coefficient of determination (R^2) shows the proportion of the variance in the measured data that is explained by the model, with values closer to 1 indicating less error variance. The regression functions had R^2 values ranging from 0.45 [7] to 0.69 [8], indicating that the regression functions did not include all of the parameters that affect the water intake of the cows. However, since values >0.5 are generally considered acceptable [24,25], all of these models were more or less acceptable. All of the previously published regression functions were based on investigations that were conducted from early to mid-lactation [7–10], and so did not cover the period of lactation when the milk yield—and hence the drinking water demand—is lower. By contrast, in the present study, the cows milked in the HBP were at the end of lactation. Therefore, this may explain why the calculated drinking water demand from all regression functions, except that of Holter and Urban [8], was significantly higher than our measured values from the HBP.

Table 2. Summary statistics for previously published regression functions and the function developed in this study for the two milking systems.

Model Evaluation Statistics	Estimated Value	Cardot et al. [7]	Holter and Urban [8]	Meyer et al. [9]	Murphy et al. [10]	This Study
Standard regression	Slope	1.30	1.54	0.94	1.33	0.97
	y-intercept	−34.36	−26.66	0.96	−38.10	1.09
	Pearson's correlation coefficient (R)	0.86	0.87	0.63	0.77	0.82
	Coefficient of determination (R^2)	0.74	0.75	0.39	0.59	0.67
Dimensionless	Nash-Sutcliffe efficiency (NSE)	−0.15	−0.53	−0.44	−1.11	0.51
	Logarithmic transformed NSE (NSElog)	−0.60	0.12	−0.56	−1.98	0.59
Error index	Root mean square error (RMSE)	15.12	14.79	17.06	17.89	12.18
	RMSE-observations standard deviation ratio (RSR)	0.80	0.70	0.84	0.71	0.57
	BIAS	9.74	−8.05	3.89	10.92	−0.01
	Percent bias (PBIAS)	13.4	−11.1	5.4	15	−0.01

Only the function developed in this study showed acceptable NSE and NSElog values of >0.5, although the function of Holter and Urban [8] also resulted in an acceptable value of >0 for NESlog; the peaks resulting from a larger drinking water demand affected this model's performance. In general, model simulation with dimensionless model evaluation statistics can be considered satisfactory if NSE > 0.50 and RSR < 0.70, and if PBIAS < 25% for streamflow [20]. By contrast, an NSE value < 0.0 shows that the mean observed value is a better predictor than the simulated value, indicating unacceptable performance. The logarithmic transformed NSE (NSElog) lowers the tendency of the NSE to overvalue large peaks.

The function developed in this study also showed the lowest RMSE, RSR, and BIAS error indices. RSR values of 0 indicate a perfect fit using the absolute error index statistic, and so the RSR values for the other functions (>0.70) must be considered unsatisfactory. Residual variance is the difference between the measured and simulated values, and is often estimated by the residual mean square or root mean square error (RMSE). The lower the RSR, the lower the RMSE, which indicates a better model simulation performance. The BIAS was larger for the previously published functions, which measures the average tendency of the simulated constituent values to be larger or smaller than the measured data.

In the literature studies of Cardot et al. [7], Holter and Urban [8], Meyer et al. [9], and Murphy et al. [10], more parameters influencing water intake were investigated than were finally included in the new regression function. It cannot be ruled out that these parameters could have a greater influence on the water intake of the cows in this study. Using the regression function of the earliest study predicted the water intake best, although the genetics, physiology, and milk yield of the cows has changed over the years. Further reasons for the difference between estimated and measured drinking water intake may be factors that were not investigated, such as rank fights, sexual cycle, and disturbance caused by external factors.

Our regression function includes only two parameters, since others such as live weight, dry matter intake, or sodium intake were not measured in this commercial dairy herd. The coefficients of the parameters in this function are not comparable with other studies, since every study includes its own parameters in the regression functions. The coefficient and hence the influence of the milk yield on drinking water intake in this study is comparable to the other regression functions. This can be explained by the interdependence of the different parameters, for example a higher dry matter intake will lead to a higher milk yield. If the dry matter intake is not included in the regression function, a part of its influence will be compensated by the milk yield parameter [26]. The R^2 of our regression function is 0.67, which lies between the R^2 of Cardot et al. [7] at 0.74 and that of Murphy [10] at 0.59.

3.2. Cleaning Water Demand

The daily cleaning water demand of the HBP and the AMS is shown in Figure 6. Neither milking system showed a seasonal pattern for cleaning water demand. The cleaning water demand was higher in the HBP than in the AMS. The daily cleaning water demand ranged from 1.1 m^3 to 18.1 m^3 in the AMS and from 1.1 m^3 to 15.2 m^3 in the HBP.

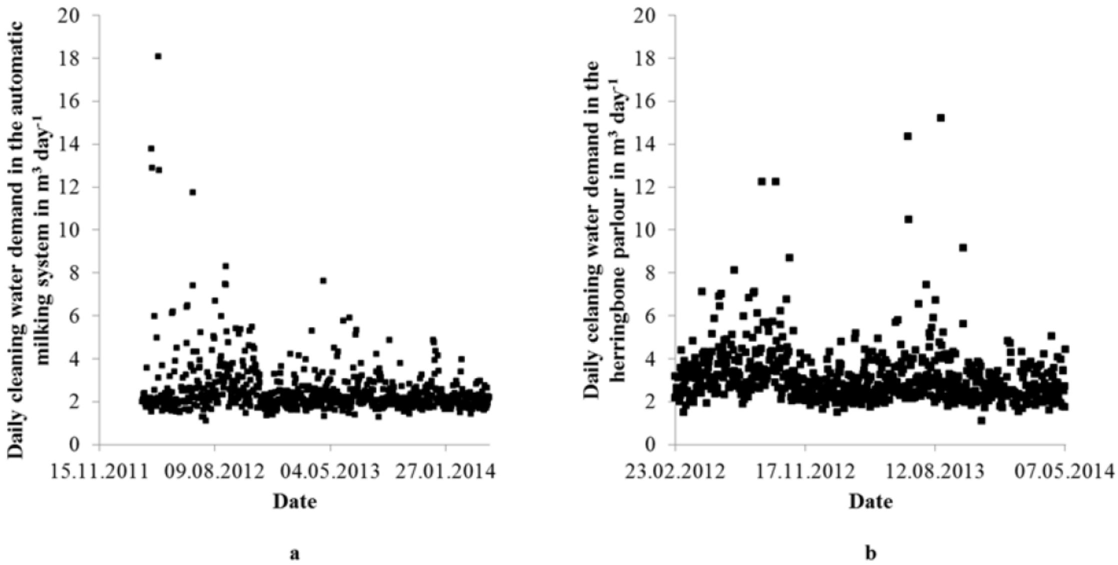

Figure 6. Daily cleaning water demand in the (**a**) automatic milking system (AMS) and (**b**) herringbone parlour (HBP).

For cleaning the AMS, on average 2.5 m^3 water was used per day (Table 3). Per cow per day, 28.6 L water was needed. Related to the milk yield of the cows, 0.8 L water was used per kg milk to clean the AMS. The cleaning of the milk tank required 0.2 m^3 water per day or 7% of the total water use in the AMS.

For cleaning the HBP, 3.1 m^3 water was used per day (Figure 6, Table 3). Per cow per day 33.8 L water was used, which is 5.2 L per day or 18% more than in the AMS. For cleaning the surface of the milking parlour 2.0 m^3 water was used. Fourteen litres of cleaning water per square metre was used in the HBP. Cleaning of the milking system required 0.7 m^3 water per day and cleaning of the udder prior to milking 0.3 m^3 per day. 0.1 m^3 water per day was used for cleaning the milk tank, which is 4% of the total technical water use. Related to the milk yield, 1.3 L per kg milk was used for cleaning.

Table 3. Comparison of the water demand of the milking systems.

Water Demand	Unit	Mean	Standard Deviation	Min	Max
Automatic milking system (AMS)					
Cleaning water demand					
per day	$m^3 \cdot day^{-1}$	2.5	1.3	1.1	18.1
per cow and day	$L \cdot cow^{-1} \cdot day^{-1}$	28.6	14.8	11.8	207.9
per kg milk	$L \cdot kg \cdot milk^{-1}$	0.8	0.4	0.4	6.1
Herringbone milking parlour (HBP)					
Cleaning water demand					
Total	$m^3 \cdot day^{-1}$	3.1	1.3	1.1	15.2
of the milk tank	$m^3 \cdot day^{-1}$	0.1	0.1	0	0.5
of the milking equipment	$m^3 \cdot day^{-1}$	0.7	0.3	0.3	6.9
for udder cleaning	$m^3 \cdot day^{-1}$	0.3	0.1	0.1	2.2
for surface cleaning	$m^3 \cdot day^{-1}$	2.0	1.1	0.9	9.3
per cow and day	$L \cdot cow^{-1} \cdot day^{-1}$	33.8	14.1	12.5	170.8
per kg milk	$L \cdot kg \cdot milk^{-1}$	1.3	0.5	0.5	6.5

Leaks amount to 1% of the measured technical water use in the barn and were mainly caused by disrupted hoses. Hose disruption seldom occurred (5 times during the observation period), but can result in high water loss if this happens at night and is only detected hours later in the morning when the first workers enter the barn.

The high cleaning water use in the HBP was caused by the cleaning system and the fact that there was no incentive to save water. The cleaning was performed with a high-pressure cleaner and a hose with a large diameter. The water was supplied via the farm's own bore, so that no costs were incurred for the water, only energy costs for pumping. Furthermore, the water was deliberately added to the slurry to keep it pumpable. This leads to high water demand for cleaning the surface of the parlour.

In the studies by Jensen [12] and Rasmussen and Pedersen [14], the cleaning water use was 0.2–0.4 L water per kg milk, which is less than half of what we measured. In their studies the AMS were optimized for low water use and were operated with the maximum number of cows. The higher water demand by the commercial farm in our study was also explained by withdrawal of water which was not directly used to clean the AMS, but to clean the barn of the cows in the AMS. Chapagain and Hoekstra [27] estimated the cleaning water demand in their calculation of the virtual water at 22 L per cow per day, which is 6.6 L less than measured in the AMS and 11.8 L less than in the HBP. A cleaning water demand of 0.3 L water per kg milk was estimated in a life cycle assessment study by Eide [28] for Norwegian conditions, which is 60% less than in this study. KTBL [13] estimated 2 L per square meter for cleaning an HBP, which is one seventh of what we measured.

In the AMS the share of drinking water demand was 76% and the share of cleaning water 24% of the total technical water demand. This is comparable with the results of Drastig et al. [1]. In the HBP, 62% of the water was needed for drinking and 38% for cleaning. The difference is explained by the higher cleaning water demand per cow and the lower drinking water demand per cow in the HBP. It is difficult to make general statements about reductions of the water demand in a dairy barn, since regression functions of the water demand only cover up to two thirds of the influencing parameters. The variation in cleaning water demand between the milking systems was less than the water demand for cleaning the surface of the parlours. Cleaning of the milking system was computer-controlled, while the surface of the parlour was cleaned by hand. The soiling depends on the cows. The water demand can be reduced by educating the workers to reduce water use, by using high-pressure cleaners or mechanical cleaning methods such as a brush. The cleaning water demand per liter of milk could be reduced with more milk milked per cleaning cycle, if the total cleaning water demand cannot be reduced. This could be achieved with more cows, if the barn allows, or higher milk yields of the cows. The findings of this study with respect to the cleaning water demand are only applicable to this particular barn with its milking and cleaning systems. Therefore, further detailed measurements in other barns are required to make general statements about methods for reducing the cleaning water demand.

3.3. Relation of Technical Water Demand to Total Water Demand for Milk Production

The relation of the technical water demand to the total water demand for milk production is shown in Table 4. The technical water demand in the HBP was 89 L per cow per day and in the AMS 121 L per cow per day. Given a water demand between 600 and 700 L per kg milk for the production of feed, according to the farm water productivity approach [2] the measured water demand for drinking was 0.4% of total water demand. The relation of cleaning water to total water demand was 0.1% for the AMS and 0.2% for the HBP. The share of the technical water demand was about 10 times higher than the share of the indirect water demand for farm buildings in total water demand of 0.05% [29]. If the water demand for feed production is estimated with a life cycle approach [30] the relation of drinking and cleaning water demand is 8.0%. Calculating the water demand for feed production according to the water footprint concept, the drinking water demand would be between 0.6% [27] and 1.1% [29] and the cleaning water demand between 0.2% [27] and 0.8% [29]. The technical water demand per cow was in the range estimated in the studies mentioned, while its percentage of the total water demand was lower due to the high milk yield of the cows. Hence the technical water demand per kg milk is low.

Table 4. Relation of technical water demand obtained in this study to total water demand for milk production from various references.

Reference	Approach	Fractions of Water Use	Total Water Demand in $L \cdot kg^{-1} \cdot$ milk	Share of Drinking Water	Share of Cleaning Water	Share of Technical Water
				of Total Water Demand in %		
de Boer et al. [30]	Life cycle assessment	evaporation of transport of feed or electricity production, evapotranspiration of feed cultivation, unused irrigation water, water embodied in crop or animal products, tap water for industrial or agricultural processes	66	-	-	8.0
Sultana et al. [31]	Consumptive water use	water consumption from feed and other inputs, e.g., drinking, servicing, manufacturing inputs and capital goods	1833	1.0	4.0	5.5
Chapagain and Hoestra [27]	Water footprint	evapotranspiration for plant growth, ground/surface water consumed, drinking and service water	735	0.6	0.2	0.8
Mekonnen and Hoekstra [32]	Water footprint	evapotranspiration for plant growth, ground/surface water consumed, drinking and service water, freshwater required to dilute the load of pollutants to ambient water quality standards	1020	1.1	0.8	2.0
Zonderland- Thomassen and Ledgard [33]	Water footprint	evapotranspiration for plant growth, ground/surface water consumed, freshwater required to dilute the load of pollutants to ambient water quality standards	1015	1.0	1.0	2.0
Peden et al. [4]	Livestock water productivity	transpiration, evaporation, downstream discharge, degradation and contamination of water	1269	<2.0	-	-
Singh and Kishore [34]	Water productivity	irrigation water use for crop production, drinking water	2040	1.2	-	-
Brown et al. [35]	Virtual water	rain water, irrigation water, the water requirements of feed, drinking and service water for animals, water required for processing	-	0.4	0.006	-
Atzori et al. [36]	Net water footprint index	evapotranspiration including rain water, soil water, and irrigation water, drinking water, service water	26–408	-	-	2–40

4. Conclusions

The technical water demand of the commercial dairy farm investigated is influenced by the milking system, the management, environmental factors, and the milk yield. The drinking water intake corresponds with the ambient temperature and the milk yield. The cleaning water demand in the automatic milking system is lower per cow per day than in the herringbone parlour. The technical water demand in the barn could be lowered by reducing the cleaning water demand. The total technical water use in the barn makes a minor contribution to water use in dairy farming compared with the water use for feed production.

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Abbreviations

The following abbreviations are used in this manuscript:

°C	degree Celsius
AMS	Automatic Milking System
ATB	Leibniz Institute for Agricultural Engineering Potsdam-Bornim
DMC	dry matter content
DMI	dry matter intake
DOY	day of the year
FTP	file transfer protocol
h	hour
ha	hectare
HBP	herring bone parlour
kg	kilogram
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
L	liter
Max	maximum
Min	minimum
m	meter
m^2	square meter
m^3	cubic meter
NSE	Nash-Sutcliffe efficiency
NSElog	logarithmic Nash-Sutcliffe efficiency
PBIAS	percent BIAS
R^2	coefficient of determination
RF	rainfall
RMSE	root mean square error
RSR	ratio of the root mean square error to the standard deviation of measured data
SD	standard deviation
T_{mean}	mean ambient temperature
T_{min}	minimum ambient temperature
In_{Na}	sodium intake
m_{b}	live weight of the animals
W_{clean}	cleaning water
$W_{\text{drink-cow}}$	drinking water of the cows
$W_{\text{drink-cow\_daily}}$	daily drinking water of the cows
W_{irri}	irrigation water
W_{tap}	tap water
W_{tech}	technical water
$W_{\text{tech-barn}}$	technical water in the barn
Y_{milk}	milk yield

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13 Eidesstattliche Erklärung

Hiermit erkläre ich, die vorliegende Dissertation selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt zu haben.

Zwickau, den 09.12.2016

Michael Krauß